REPORT

THE ESSENTIAL DROP TO REACH NET-ZERO:
Unpacking Freshwater's Role in Climate Change Mitigation

Freshwater can make or break our ability to successfully implement many climate change solutions. This report presents why, where, and how freshwater should be integrated into climate change mitigation plans and activities.

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Acronyms

AFOLU	Agriculture, Forestry and Other Land Use
BECCS	Bioenergy with Carbon Capture and Storage
BCE	Blue Carbon Ecosystems
BMZ	German Federal Ministry for Economic Cooperation and Development
CBD	Convention on Biological Diversity
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CO_2	Carbon Dioxide
COP	Conference of the Parties
EbA	Ecosystem Based Adaptation
FAO	Food and Agriculture Organization of the United Nations
FLR	Forest Landscape Restoration
FSC	Forest Stewardship Council
GCF	Green Climate Fund
GEF	Global Environment Facility
GGW	Great Green Wall
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH)
GWP	Global Water Partnership
IEA	International Energy Agency
IHA	International Hydropower Association
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IUCN	International Union for Conservation of Nature
IUWM	Integrated Urban Water Management
IWA	International Water Association
IWRM	Integrated Water Resources Management
LCA	Life Cycle Assessments
LULUCF	Land use, land-use change, and forestry
LTS	Long-Term Strategies
MEA	Multilateral Environmental Agreement
MDG	Millennium Development Goals
NAP	National Adaptation Plan
NbS	Nature-based Solutions
NBSAP	National Biodiversity Strategies and Action Plans
NDC	Nationally Determined Contributions
NGO	Non-governmental Organizations
NZE	Net-Zero Emission
ODA	Official Development Assistance
OECD	Organisation for Economic Co-operation and Development
PES	Payment for Ecosystem Services
PIK	Potsdam Institute of Climate Impact Research
PV	Photovoltaics
REDD	Reduce emissions from deforestation and forest degradation
RCP	Representative Concentration Pathway
S2S	Source-to-Sea
SDG	Sustainable Development Goal
SIWI	Stockholm International Water Institute
SLM	Sustainable Land Management
UNCCD	United Nations Convention to Combat Desertification
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WaCCliM	The Water and Wastewater Companies for Climate Mitigation
WASH	Water Sanitation and Hygiene
WEF	Water-Energy-Food
WER	Warsaw Framework for REDD+
WHO	World Health Organization
WMO	World Meteorological Organization
WRI	World Resources Institute
WWF	World Wide Fund for Nature
WWTPs	wastewater treatment plants

Foreword

Whether blue or green, freshwater is an undervalued factor in climate change mitigation. With this report, we aim to build understanding and inspire informed decision-making by identifying opportunities, risks and critical knowledge gaps based on the best available scientific knowledge.

Pioneering work is urgently needed to design climate policies. Climate mitigation will not work without including water, and decision-makers need to find ways to understand, plan, and account for the water needed for healthy ecosystems and prosperous societies. That is why water must be protected from uninformed mitigation planning which could have serious unintended consequences.

This report explores complex interconnections between water and climate within several sectors and biomes of society, including water systems, energy systems, and aquatic and terrestrial systems. It highlights powerful solutions for working alongside nature to mitigate climate change, whilst achieving other important benefits. The report also points to the untapped mitigation potential of the water sector.

It is our ambition that *The essential drop to reach Net-Zero: Unpacking Freshwater's Role in Climate Change Mitigation* will contribute to better use of water in the actions needed for achieving climate neutrality. Also, that this report will also inspire and encourage further research, gaining an even better understanding of the critical role of water for climate mitigation.

Finally, the time for water to be mainstreamed into climate mitigation planning is now. Without accounting for water, climate mitigation cannot be achieved at the pace and scale required. By taking a more holistic view, this report points to the critical importance of this message and sets a clear pathway to action.

We urge the climate and water community alike to respond to this call.

Thomas Rebermark,
Director Swedish Water House,
Stockholm International Water Institute

Sunrise over a misty lake, northern Latvia. Source: Shutterstock.

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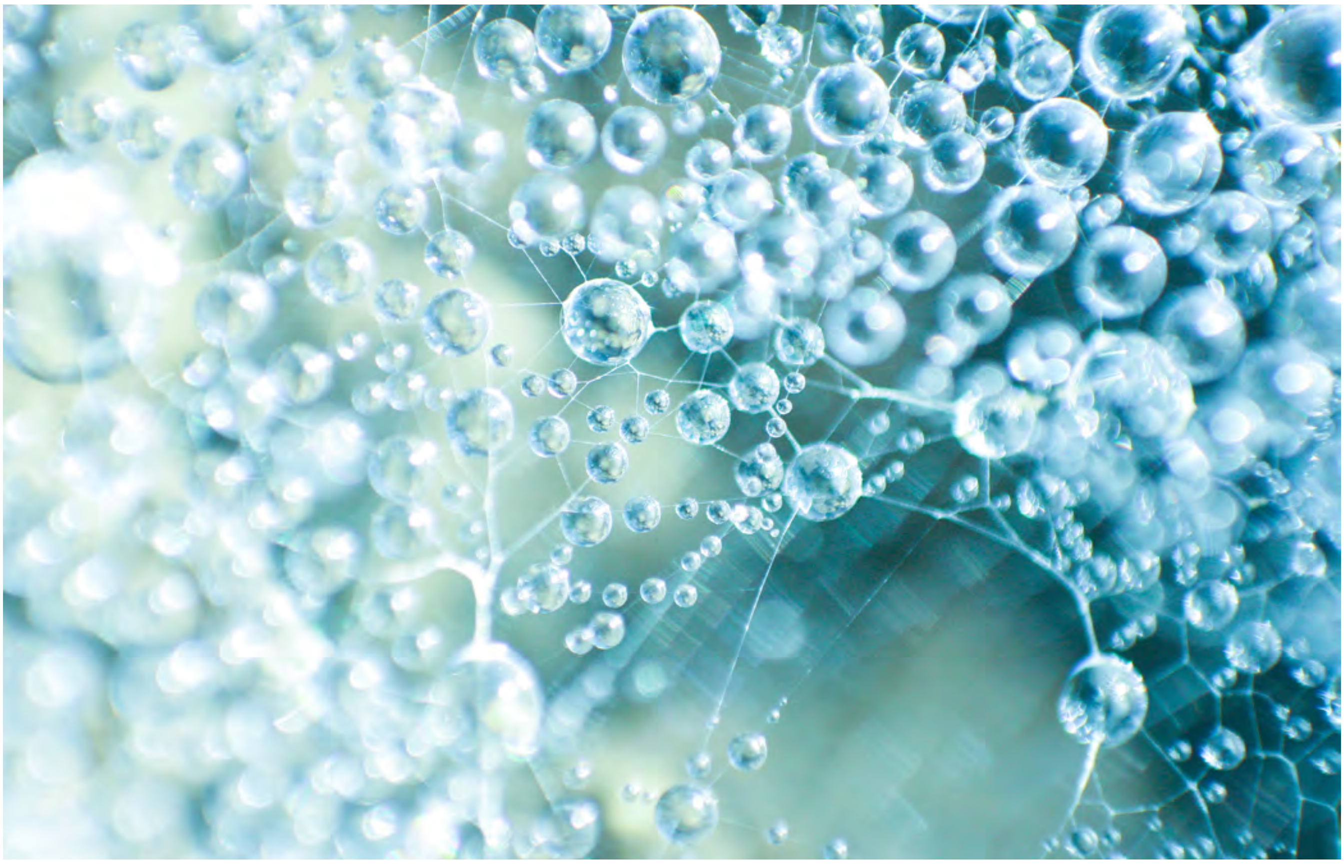
KEY MESSAGES AND EXECUTIVE SUMMARY

Unpacking Freshwater's Role in Climate Change Mitigation

Key Messages and Executive Summary Contents



Water is the foundation of successful mitigation action as Earth's climate system and water cycle are deeply intertwined. Source: Shutterstock.

Key Messages

Water must be mainstreamed into climate mitigation planning. Sustainable water management across key sectors is essential to achieve the Paris Agreement mitigation targets. This report identifies high-potential opportunities for water-related mitigation action, and further examines water-related risks which need to be assessed to ensure that mitigation actions can be sustainable and account for water. Climate mitigation cannot be achieved at the pace and scale required unless it is water-wise. Such water-wise climate mitigation planning integrates the understanding of the following five report key messages.

1. **Climate mitigation measures depend on freshwater resources.** Present and future freshwater availability needs to be accounted for in climate mitigation planning and action.
2. **Climate mitigation measures impact freshwater.** Freshwater impacts – both positive and negative – need to be evaluated and included in climate mitigation planning and action.
3. **Water and sanitation management can reduce GHG emissions.** Climate mitigation planning and action should include the substantial emission reduction potential in drinking water and sanitation services, and through the management and protection of freshwater resources.
4. **Nature-based solutions to mitigate climate change can deliver multiple benefits for people and the environment.** Priority should be given to measures that can safeguard freshwater resources, protect biodiversity, and ensure sustainable and resilient livelihoods.
5. **Joint water and climate governance need to be coordinated and strengthened.** Mainstreaming freshwater in all climate mitigation planning and action requires polycentric and inclusive governance arrangements that can facilitate integrated approaches.

Key benefits of taking action on these key messages are provided below:

1. Climate mitigation measures depend on freshwater resources

Present and future freshwater availability needs to be accounted for in climate mitigation planning and action in order to:

Assess and coordinate sustainable freshwater demands across climate mitigation measures

The success of most mitigation measures relies substantially on freshwater availability and quality, as well as sustainable water management. Freshwater, however, is a finite resource already over-exploited in many places, and climate change is increasing the pressure on water resources even further. Mitigation planning and action must therefore urgently, and increasingly, understand and consider both freshwater availability and constraints for climate mitigation. Considerations for water cannot only be integrated in individual measures or sectors, but sustainable demands need to be coordinated and determined across measures and sectors.

Navigate water-wise energy transitions

The energy sector, in particular, needs to account for freshwater availability while planning transitions to low-emission sources. Most energy production requires substantial amounts of water, and this includes significant water use in renewable energy: hydropower, bioenergy, and thermal energy generation from solar, geothermal, and nuclear power. Comprehensive analysis of actual water availability, projected water demands and savings, as well as technologies and impacts to assess options at local, national, regional, and global level is needed when assessing current and future energy alternatives. These assessments must consider competing water demands, including those for ecosystem needs, as well as potential changes to water availability caused by ongoing climate change.

Protect water for nature

The success of nature-based solutions, including the mitigation potential of aquatic and terrestrial ecosystems, are intrinsically interlinked with freshwater availability and the water cycle. These natural processes are subjected to strong changes under current and future environmental changes. For instance, improved protection and management of wetland or forest water cycles can avoid the risk of turning ecosystems from carbon sinks into carbon sources. Similarly, sustainable water management plays a key role in safeguarding already sequestered carbon in croplands and managed grasslands, such as by maintaining existing soil carbon stocks through sustainable management of these multifunctional landscapes.

2. Climate mitigation measures impact freshwater

Freshwater impacts – both positive and negative – need to be evaluated and included in climate mitigation planning and action in order to:

Consider water risks and environmental impacts of climate action

Climate change mitigation efforts can have negative impacts on freshwater balances and the water cycle, leading to reduced or polluted water resources, as well as degraded ecosystems – whose services we oftentimes rely on to generate the water resources. These negative impacts are therefore critical to consider when determining the specific type of mitigation measure, for example when selecting a suitable renewable energy source or determining the viability of plant growth for carbon storage. The production of bioenergy is of particular importance as questions around quantity, location, crop species, and production technique all have potential large impacts on water cycling and availability, and land use overall.

Manage and minimise trade-offs between mitigation potential and water risks

Analysis of trade-offs between mitigation potential and impacts on freshwater resources and implications for future water security is critical. Climate mitigation potential needs to be weighed against the risks of degrading water cycles and polluting or over-abstracting freshwater resources. For instance, reservoirs created by hydropower dams may emit significant amounts of GHG, depending on factors such as organic content and nutrient loading, reservoir sediments, primary productivity, and water temperature, but also the characteristics of the reservoirs themselves (local

The Hoover dam in the USA provides clean hydropower but negatively impacts the local hydrological system Source: Shutterstock.

temperature, depth, etc.) and their catchments (land use, human activities, etc.). Plantations of fast-growing, water-demanding tree or crop species, for carbon storage or energy production, is another example of a mitigation trade off that requires risk assessment, as well as know-how on sustainable water management that may mitigate those risks. Poorly planned implementation of mitigation measures can cause local water shortage, biodiversity loss, and harm to local communities and livelihoods.

Maximise synergies and co-benefits across sectors

Climate mitigation efforts that have positive impacts on freshwater balances often also benefit other values, such as climate adaptation, livelihoods, and biodiversity. For instance, protecting and restoring aquatic ecosystems, such as wetlands, can mitigate climate change, while also supporting the water cycle, improving the health of nearby ecosystems, and reducing impacts of droughts and floods. Similarly, mitigation measures in land systems – such as agroforestry, ecosystem restoration, and improved soil carbon management – have the potential to increase groundwater recharge and increase water vapour exchange with the atmosphere, thereby enhancing local cooling and regional rainfall, while also boosting crop production and resilience to a changing environment. A water-wise perspective in climate mitigation can therefore present an opportunity to improve climate mitigation potential, while also enhancing other benefits such as water security and both human and ecosystem health.

3. Improved water and sanitation management reduces GHG emissions

Climate mitigation planning and action should include the substantial emission reduction potential in drinking water and sanitation services, and through the management and protection of freshwater resources. This requires actions to:

Measure, report and reduce emissions, and recover energy in water and sanitation services

Drinking water and sanitation services account for a significant share of GHG emissions, and implementations of targeted GHG mitigation actions exist. Direct GHG emissions from wastewater and faecal sludge can be reduced through the improved design, management, and adjustment of operating conditions of WWTPs, while energy efficiency measures in water supply and sanitation can greatly reduce indirect emissions. For instance, technology-based solutions and new treatment configurations and processes, low-carbon energy created from wastewater management, and extension of wastewater collection and treatment systems, including decentralised solutions, can serve to meet mitigation targets. There is also mitigation potential in the transition to low emission energy sources, resource recovery and energy generation from wastewater, circular systems of reusing and recycling water and wastewater, and improved efficiency and management of water supply and distribution. In addition, significant techniques and tools already exist to strengthen assessment, monitoring, and reporting of GHG emissions from water and wastewater. Available tools, guidance and technologies for enhanced climate mitigation potential should be scaled up via investment and training.

Accurately account for and reduce GHG emissions from polluted freshwater systems

Critical gaps in data and reporting lead to the likely underestimation and under prioritisation of GHG emissions from water supply and sanitation. It is crucial to ensure that these emissions are accounted for by supporting data-gathering and inventory of CO_2, CH_4, and N_2O emissions, from water and wastewater utilities, and untreated wastewater in aquatic environments. It is also needed to strengthen emissions reporting and integration into national GHG inventories. The process of untreated wastewater degradation can entail the release of GHGs into the atmosphere. Therefore, wastewater treatment and discharge for domestic and industrial sectors should be reported, as should emissions from untreated wastewater. Underestimation of the emissions released from water bodies polluted by untreated wastewater, and data and reporting gaps on wastewater treatment globally, may result in these emissions not being included in national GHG accounting. By extension, it does not properly incentivise actions to reduce emissions through, for instance, dry sanitation solutions. Wastewater treatment can cause these same emissions plus additional emissions from fossil energy consumption (e.g., anaerobic lagoons or basic sanitation solutions). There is high potential to reduce these emissions by climate friendly approaches of wastewater treatment (e.g., biogas production and flaring, or even utilisation).

Mangrove restoration at the Trapeang Sankae Mangrove Sanctuary in Kampot, Cambodia. Source: Shutterstock.

4. Nature-based solutions to mitigate climate change can deliver multiple benefits for people and the environment

Priority should be given to measures that can safeguard freshwater resources, protect biodiversity, and ensure sustainable and resilient livelihoods by working to:

Support nature's ability to sequester and store carbon

Nature-based solutions (NbS) have a critical role to play in meeting climate mitigation targets. They involve measures of protecting, restoring, and better managing ecosystems, including ecosystems' natural capacity to absorb and store atmospheric carbon, while maintaining or enhancing biodiversity and ecosystem services. The availability of rainwater and soil moisture is critical for the ability of terrestrial ecosystems (e.g. forests, grasslands, croplands, shrublands, and savannas) to maintain carbon uptake. Similarly, 'blue carbon' ecosystems (saltmarshes, seagrass meadows and mangroves) are highly productive with the potential to capture 0.5%-2% of global carbon emissions in the biomass of living organisms, soil, and sediments. Also noteworthy, nutrient pollution causes lakes, rivers, and reservoirs to emit GHG, while intact water bodies can act as GHG sinks. Reservoirs created by dams, with fluctuating water tables and a high occurrence of organic material, produce considerably more methane than natural lakes or other surface waters. Good water management is also critical to ensure the productivity and carbon storage potential in land systems, such as forests, croplands, and grazing lands.

Protect the water cycle to sustain critical carbon sinks

Changes in freshwater dynamics risk compromising the effectiveness of nature based mitigation. An intact water cycle is required to achieve full mitigation potential and to ensure long-term carbon storage. Climate change-induced decreases in soil moisture can limit the capability of plants to store carbon, both below- and above-ground. Examples include conserving and restoring wetlands, forests including coastal mangroves, and natural floodplains in water courses to protect these net sources of GHGs. For example, peatlands only cover about 3% of the world's land surface but store at least twice as much carbon as all of Earth's forests, while mangrove soils can sequester up to 3-4 times more carbon than their terrestrial counterparts. Policies need to facilitate immediate water-wise actions and management that restrict the drivers of ecosystem degradation and loss, such as conversion to agriculture, urbanisation, aquaculture, or coastal development.

Value benefits from NbS beyond carbon sequestration

NbS are often low-cost, and dependent on sustainable and water-wise management of ecosystems and their services. Ecosystems' carbon sequestration is a key NbS that with the right planning and management can have multiple synergistic benefits for people, the economy, and the environment. In order to optimise the impact of an NbS, it is necessary to consider and manage the trade-offs from expected benefits. For instance, the strategy for restoring a forest or a wetland will be different depending on the goal of the restoration effort; restoration to enhance mitigation potential requires one set of species, while restoration to enhance biodiversity may require a different set of species. Effectively and equitably conserving Earth's terrestrial and freshwater habitats, and restoring degraded ecosystems, leverages nature's capacity to absorb and store carbon and mitigate climate change. It can further accelerate progress towards sustainable development. Adequate finance and political support are essential to direct and prioritise action to protect natural systems to provide these benefits.

5. Joint water and climate governance needs to be coordinated and strengthened

Mainstreaming freshwater in all climate mitigation planning and action requires polycentric and inclusive governance arrangements that can facilitate integrated approaches. This requires policymakers to:

Embrace integrated approaches to climate mitigation

Efforts are needed to establish water coordination mechanisms with other governance processes, particularly when setting Nationally Determined Contributions (NDC). This is to facilitate participation of all relevant ministries and other actors to design more polycentric and inclusive governance frameworks, which enable and support integrated approaches that move away from siloed problem-solving. Effective emission reduction strategies will entail coordinated approaches for land and water management, whilst also considering factors such as disaster risk reduction, biodiversity recovery, and sustainable community livelihoods. Better aligning the planning and goal setting would leverage synergies across sectors where relevant.

Enhance governance across levels and sectors

There is a strong need to adapt water and climate governance frameworks and instruments to different contexts. Some situations, like the provision of drinking water and sanitation services, require decentralised solutions resting on local governance - encouraging equitable and efficient water use. Other contexts, like the management of aquatic environments and forests, require watershed-level governance. Governance frameworks and instruments need to be developed transparently with local actors in order to be coherent with local circumstances. There is also a strong need for better coordination and collaboration between stakeholders, sectors, and in the case of transboundary watersheds, also countries, to help achieve and share benefits, and to address trade-offs and conflict.

Effective governance and regulatory frameworks - those that have been developed through consultative processes and rhyme with collective goals and aspirations of societies - can have dramatic positive effects in aligning individual action towards greater societal goals like good water governance, adaptation and mitigation of climate change.

Enable knowledge-based decision-making through data generation, harmonisation, and transparency

There is a critical need to improve the quality and coverage of scientific data to enable mainstreaming of water into climate mitigation and improve the capacity of managers and policymakers to make well-informed decisions. For example, information and reporting gaps currently lead to a likely underestimation and under-prioritisation of GHG emissions from water supply and sanitation, despite available measurement and reporting tools. Similarly, improvements in biophysical data collection and coverage at different scales are key to ensure that inland water bodies, wetlands, and coastal systems are more commonly included within the GHG inventories, in terms of emissions or storage. Harmonisation across accounting methodologies to ensure consistency is also needed. Even when data is available, transparency and data-sharing need to be improved, requiring efforts to strengthen disclosure and enhance the scientific knowledge underpinning the generation of robust data. Collaboration should be fostered to drive disclosure, as well as cost-efficient data collection. There is a need to build institutional and citizen capacity to strengthen data collection, management, and sharing capacities. This includes improving frameworks and knowledge to better utilise digital solutions, data management systems, and build capacity to develop integrated and cross-sectoral data collection and monitoring systems.

Build capacity through inclusive knowledge systems

Building capacity to better understand the increasingly complex interdependencies across scales and actors is fundamental. A great majority of mitigation measures worldwide – including in ecosystems, food systems, and energy systems – influence, or are influenced by, water management and water availability in ways that must be understood and planned for. Building capacity to strengthen and integrate knowledge is therefore critical. Capacity can be strengthened by learning across governance systems and leverage existing governance regimes. For instance, by building upon the strong global frameworks that exist for climate action and the robust national plans that often exist for water management. Overall, it is fundamental that measures to build capacity are inclusive, paying special attention to youth, women, and vulnerable groups.

Strengthen water-wise climate governance to tap into existing climate funds

There is an untapped potential to access international climate finance for water related mitigation measures. Currently, large sums are being committed at the international level to mitigate and adapt to climate change, but only a small fraction of these funds are being directed to water-related mitigation measures. There is an opportunity to tap into these funding sources and redirect funds for investments in water-related projects, if such mitigation measures are integrated into the NDCs and other national and sectoral instruments. Most financing committed today, however, is mobilised at the national level; there is still a substantial need to mobilise additional financing for local projects, particularly in low-income countries. Additional investments are needed in all sectors: for wastewater treatment, improved energy efficiency and use of renewable energy in water utilities, sanitation services, for restoring degraded aquatic environments, forests, and agricultural lands. To meet these funding demands, new pathways need to be explored that can facilitate investments and direct funding into areas that can support water-related mitigation measures. This will require action to foster innovative financing models that can incentivise commercial, as well as non-commercial, sources of funding that can make targeted investments to benefit those most vulnerable. It is critical that the water sector alone does not carry the sole fiscal responsibility for delivering projects upstream with substantial climate mitigation potential.

Concluding statement: We need to act now

The earlier we act on water and climate jointly; the more synergies can be reaped, and trade-offs avoided. Limiting global warming to 1.5 degrees is still narrowly within reach, and water across terrestrial, aquatic, and technological systems, plays a critical role for the necessary transformation towards net-zero.

Executive Summary

In the Sixth Assessment Report on Mitigation of Climate Change, the International Panel on Climate Change (IPCC) makes it clear that we need to act now: the findings show that greenhouse gas (GHG) emissions continue to rise, and current plans to address climate change are not ambitious enough to limit global warming to 1.5°C above pre-industrial levels – a limit necessary to avoid even more catastrophic impacts on people and ecosystems (IPCC 2022). With every fraction of a degree of global warming, climate change impacts will intensify. The IPCC therefore calls for an immediate and complete transformation of every sector of society. Emissions must peak by 2025 to achieve the 1.5° target as agreed in the Paris Agreement, and to reach the goal to halve greenhouse gas emissions by 2030 (UNFCCC 2015). Consequently, countries and companies are pledging to reach 'climate emissions neutrality' or 'net-zero greenhouse gas emissions', to try and achieve a balance between the carbon emitted into the atmosphere, and the carbon removed from it, which is in line with the 1.5° target. To that end, the IPCC has identified numerous climate mitigation measures that can provide a pathway to achieve rapid transition to net-zero emissions. Many of these measures have a direct link to freshwater.

Water is the foundation of successful mitigation action, as Earth's climate system and water cycle are deeply intertwined. Many of the transformations needed to reach climate emissions neutrality:

1. depend upon a reliable access to freshwater

2. will have a significant impact on freshwater resources and/or ecosystems.

Functioning freshwater systems are essential for climate mitigation through measures such as reforestation, restoration of degraded ecosystems, and bioenergy with carbon capture and storage (BECCS). Some potential climate solutions even risk reducing mitigation effects if plans fail to assess and minimize water risks. Hydropower facilities with poor citing, design, and management, for example, can result in less power generation and greater emissions from impacted reservoirs. This is particularly important as most mitigation measures worldwide have an impact on freshwater resources and ecosystems. Therefore, the transformations of, for example, our food and energy systems must be accompanied by comprehensive analyses of water availability and impacts at local, regional, and global levels. At the same time, the water sector itself offers untapped mitigation potential: climate smart water management, for instance, can significantly avoid and reduce emissions of carbon, methane, and nitrous oxide, emanating from urban water and wastewater management, and mismanaged or drained wetlands.

Nevertheless, the critical role of freshwater in climate mitigation is often overlooked for a number of reasons. A primary barrier is knowledge gaps of the complex


Freshwater stream. Source: Shutterstock.

Freshwater flows through different governmental jurisdictions. Source: Shutterstock.

direct and indirect interrelations between freshwater and climate mitigation at global, national, and local levels. Additionally, data gaps are leading to challenges for quantifying the climate mitigation potential. These knowledge or information gaps can lead to water-related risks and impacts not being considered at all, or only partially, in mitigation actions. There are also conceptual and structural challenges in global sustainable development governance; water and climate mitigation are treated as separate issues, governed by different governance frameworks and instruments. Furthermore, the fragmented nature of global water governance creates challenges when aligning water action with climate mitigation actions in ways that create synergies and avoid negative trade-offs. Prevailing siloed approaches, i.e., a setup where interlinked issues such as climate, water, land, and sustainable development are conceptualized, governed, and financed separately, lead to missed opportunities for climate mitigation and pose risks to the successful implementation of measures taken, as well as fail to prevent and consider possible trade-offs. By extension, the siloed approaches create barriers to climate mitigation. Integrated approaches are needed to overcome these barriers by identifying opportunities to reduce emissions and water stress, as well as to ensure that actions taken are resilient to water risks. Big investments in the many win-win solutions for climate and water security are necessary, while proceeding carefully where the potential for steep trade-offs is high.

Freshwater is essential to reach net-zero greenhouse gas emissions. In this report, we explain how the journey towards climate security requires massive, cross-sectoral efforts in improved management of water. It focuses on:

1. Climate mitigation measures that require or modify freshwater sources or freshwater-dependent social-ecological systems.

2. Climate mitigation options within the water and sanitation sector with upscaling potential.

The report also addresses the multiple freshwater-related synergies and trade-offs that exist between climate mitigation and adaptation measures, as well as other benefits of water-wise mitigation actions that work with nature and contribute to sustainable development, such as enhanced system resilience, functioning ecosystems, and enhanced biodiversity. The findings attest to the urgent need to improve the understanding of the links between the many different climate mitigation measures, freshwater availability, and water management. While reviewing mitigation measures across sectors and biomes, for instance, in natural ecosystems, food production systems, and energy systems, the report provides guidance on how to move forward. It identifies high-potential water-related mitigation opportunities across the sectors and biomes where water management and Nature-based Solutions (NbS) can contribute to reduce GHG emissions and thus global warming. It further points out water-related risks to be avoided in mitigation planning, to prevent uninformed and therefore unsustainable GHG mitigation planning from negatively impacting water resources.

To that end, the report is structured as follows:

Part I: Setting the Scene on Freshwater's Role in Mitigation: A Physical Science and Governance Background

Part I of the report provides a background and context by introducing the biophysical interdependencies of freshwater's role for climate mitigation, and the governance context of climate mitigation measures.

Chapter 2. Freshwater's role for climate mitigation - the biophysical interdependencies

Chapter 2 focuses on the intricate relationship between climate and water in the larger context of the Earth system. It explains how **climate mitigation measures fundamentally depend on, and impact, freshwater resources and the water cycle**, and why a functioning freshwater cycle is crucial for climate mitigation measures to reach their full potential. For example, water stress can hamper energy production from hydropower, trigger carbon release from degrading forests, and hamper climate mitigation effects expected from measures such as protecting or sustainably managing these systems. Climate mitigation measures also can directly modify land, climate, and water quality and quantity. For instance, irrigation dependent plantations with measures such as BECCS, could unintentionally deplete local water resources, with detriments to the original ecological and carbon sequestering functioning of the impacted ecosystems. These changes happen on top of already shifting freshwater dynamics, such as droughts and floods caused by ongoing climate change. Combined, they could potentially trigger abrupt and irreversible ecohydrologic regime shifts that may not only affect the implementation and success of mitigation measures, but also threaten water security as a foundation of life for humans and ecosystems. In the dynamic and hyperconnected Anthropocene, the relationships between water and climate mitigation can be remote, complex, and nonlinear. Holistic system thinking approaches are thus needed to account for freshwater's role, both in and for climate mitigation, to be able to take decisive and sustainable action.

Chapter 3. Governance context of water-related climate mitigation measures

Chapter 3 illustrates that **strengthening governance is at the core of achieving water-wise climate mitigation**. The chapter provides an overview of the global governance frameworks and national instruments relating to climate change, biodiversity, land, water, and sustainable development including the United Nations Framework Convention on Climate Change (UNFCCC), the 2015 Paris Agreement, the Convention on Biological Diversity (CBD), the Convention to Combat Desertification (UNCCD), the Ramsar Convention, the UN Watercourses Convention, and the 2030 Agenda for Sustainable Development. The chapter also covers various financing mechanisms and instruments available to realise the goals outlined in these frameworks. The review illustrates that as interlinked issues such as climate, water, biodiversity, land, and sustainable development generally tend to be conceptualised, governed, and financed separately, siloed approaches become the norm. By extension, it creates barriers to achieve climate mitigation as leverage points are not capitalised on, and risks are not accounted for. It also highlights that integrated approaches are needed to overcome these barriers. **To better leverage connections, it is necessary to more clearly understand and articulate synergies between issues and create links between different governance structures to facilitate integrated approaches that can capitalise on these synergies**. Failing to do so is a missed opportunity for climate change mitigation we cannot afford.

Part II: Water-related mitigation opportunities across biomes and sectors

Part II of the report provides an analysis of climate mitigation measures, keying in on their use of, and impacts on, freshwater and freshwater-dependent systems. This is done by mapping the climate mitigation potential, and associated opportunities and risks, in different biomes and sectors, including drinking water and sanitation services (Chapter 4), freshwater ecosystems, and freshwater-dependent coastal and marine systems (Chapter 5), terrestrial ecosystems (Chapter 6), and energy systems (Chapter 7). These chapters examine the effects of water-related feedbacks on mitigation outcomes, as well as trade-offs and synergies between water-related mitigation and adaptation measures. Each chapter identifies knowledge gaps for characterization and quantification of water's role for climate mitigation, and offers recommendations to either reduce potential water risks in mitigation measures or enable actions that provide multiple benefits to freshwater sustainability and climate mitigation.

Chapter 4. Mitigation measures in drinking-water and sanitation services

Chapter 4 illustrates how **reducing the release of GHGs in drinking water and wastewater management presents major opportunities for climate change mitigation**. The chapter examines the mitigation potential and risks in these measures, including abstraction, treatment, distribution and discharge, and accounting for both direct and indirect GHG emissions including the electricity consumption associated with indirect carbon emissions. For instance, significant amounts of GHGs from wastewater and faecal sludge can be reduced through the improved design, management, and adjustment of operating conditions of wastewater treatment plants. Energy efficiency measures, along the water and wastewater management cycle, can be implemented to decrease energy consumption and related CO_2 emissions. Experience from water utilities, which have started to measure, reduce, and report their GHG emissions, needs to be scaled up to decarbonize water and wastewater management. Yet, a significant proportion of the wastewater generated in cities and rural areas remains untreated or only partially treated, with the emissions from untreated wastewater being an estimated three times higher than emissions from conventional wastewater treatment plants. The extension of wastewater collection and treatment systems, including decentralized solutions, emerges as a win-win for development and climate mitigation. **The actual mitigation potential of this sector is largely unknown because data on GHG emissions is limited and has high levels of uncertainty**, resulting in hampered efficiency in the integration of drinking water and wastewater management in climate policies and mitigation strategies. Thus, strengthening the assessment, monitoring, and reporting of GHG emissions from water and wastewater handling, including on-site sanitation, must be a priority for better GHG estimates and access to climate finance.

Wastewater treatment tank. Source: Shutterstock.

Chapter 5. Mitigation measures in freshwater ecosystems

Chapter 5 examines mitigation potential and risks in freshwater ecosystems. **Aquatic environments, such as freshwater peatlands, marshes, swamps, lakes, streams, rivers, and tidal wetlands, can function as either GHG sources or sinks**, depending on, for example, land use, pollution, human activities, hydrologic regime, and climate change. Wetlands, for instance, have one of the highest stores of soil carbon in the biosphere, storing more than 30% of the estimated global carbon emissions, making conservation and restoration measures crucial for the protection of these carbon stocks. To account for the emission reduction services from freshwater systems, it is necessary to include them as part of a portfolio of measures to reduce GHG emissions alongside sectors outside of land use. In addition, catchment and coastal zone scale policies, programmes, and investments should be adopted to support effective and sustainable emission reduction strategies. GHG emissions in aquatic systems are fuelled by inputs from watersheds.

Therefore, **effective emission reduction strategies may entail integrated approaches for land management, restricting nutrient loading (including improved water treatment capacities), maintaining, and improving ecohydrologic connections**. It is important to note that aquatic systems provide many other valuable services in addition to carbon sequestration, such as water quality control and flood risk reduction. Natural climate solution schemes should be designed with holistic system thinking, including the full range of ecosystem services alongside carbon sequestration. For efficient climate mitigation, emission reduction goals need to be given greater emphasis: in broad water resources management strategies; financing mechanisms; and tools need to be in place to monitor and reduce emissions at the local, regional, and national level; while capacity building and other forms of support, including better data of aquatic environments, is needed to materialise implementation.

Chapter 6. Mitigation measures in land systems

Chapter 6 examines mitigation potential and risks in land systems. Climate mitigation in land systems is primarily achieved through the binding of carbon to soil and below- and above-ground biomass in for example forests, grasslands, and croplands. Thus, land systems hold high carbon emission reduction potential, including restoration, afforestation/reforestation, prevention of land degradation or deforestation, as well as various land management approaches. However, **the success of mitigation measures in land systems relies substantially on the water cycle and freshwater availability**. For example, unsustainable management of carbon-rich soils such as excessive grazing, unsustainable logging, or fluctuating surface-groundwater can cause a shift from a GHG sink to a source of emissions. In addition, land systems are already now subject to hardly predictable and unfavourable environmental changes under rising global temperatures. Mitigation in land systems must adapt to the local hydrological, climatic, and social-ecological contexts, including the political economy, in order to generate co-benefits and minimize trade-offs between sustainability goals. This includes accounting for local warming (e.g., boreal forests absorb more radiation than boreal shrubs) and soil carbon emissions from agriculture and afforested peatland areas. This also includes accounting for land management effects on water cycle dynamics, both directly (e.g., irrigation, drainage) and indirectly (e.g., harvest rate, choice of tree or crop species, degree of collaboration with local communities). **Climate change has already substantially altered land systems' water cycles**. For instance, the carbon sink strength in tropical forests has recently peaked while the growth in the mid latitude forest carbon sink strength appears to be slowing in recent decades. Continued deterioration of the regulating effect of forests on the water cycle risks lowering agricultural productivity regionally and globally, causing irreversible damage to biodiversity, and turning the forest carbon sinks into carbon sources.

Mitigation measures in land systems can have notable synergies but also trade-offs with local-to-regional water sustainability goals. Land system mitigation measures have the potential to decrease flood risks, increase groundwater recharge, and increase water vapour exchange with the atmosphere, thereby enhancing local cooling and regional rainfall. Misguided implementation of land system mitigation measures can, on the other hand, cause local water shortage, biodiversity loss, and harm to local communities.

Sweet sorghum is used for biofuel production and has a low water requirement. Source: Shutterstock.

Chapter 7. Mitigation measures in energy systems

Chapter 7 examines the water-related climate mitigation potential and risks of low emission energy transition plans, highlighting the need to include an analysis of projected demands, availability, and impacts on freshwater, including the potential risks to water availability caused by climate change. **The transition toward low emission energy can reduce pressure on water, however, this will depend on the future mix and management of energy sources**. Water is a significant consideration for all energy production except possibly wind power and solar photovoltaics (PV). Excluding hydropower, 70% of water used by the energy sector goes to fossil fuels and thermal power generation plants. The transition to renewable energies can provide opportunities to reduce pressure and impacts on water resources from the energy sector, primarily due to the low water demands from solar PV and wind versus fossil sources. On the contrary, low-emission scenarios with high demand for 'negative emissions', i.e., activities that remove carbon dioxide from the atmosphere, imply an increase in water consumption particularly for bioenergy, with large ranges in potential water requirements (for irrigation). Sustainable water management in bioenergy with carbon capture can, in certain contexts and well-managed systems, provide both energy and climate mitigation benefits, but it is critical to consider factors such as extent, type and location of the bioenergy production for the impact on the global water cycle. Besides bioenergy, hydropower and thermal energy generation – from solar, geothermal, and nuclear power – are low-emission energy sources that have substantial water requirements. To ensure sustainability, the benefits provided by these options must be weighed against potential water risks and impacts on freshwater ecosystems. Impacts of climate change on the availability of water for cooling thermal power plants and hydropower generation are key concerns for resilient energy planning and operations. To enable the transition to renewable energies, strategies are also needed to mitigate potential water risks for energy storage solutions, including pumped hydropower, as well as mining for minerals such as copper, cobalt, lithium, and rare earth materials. **Low emission energy scenarios often lack quantification of impacts on water quality and ecosystems, which must be incorporated into national and regional planning**.

Part III: Integrating freshwater into climate change mitigation planning and action

Part III of this report draws cross-sectoral conclusions building on the findings in Part II, identifying priority risks and opportunities for water-wise climate planning, including 'win-wins', i.e., significant co-benefits to reduce the use and pollution of water bodies. Further, it explains how integrated approaches are required to account for freshwater-climate mitigation interconnections to achieve water-wise climate mitigation and presents leverage points to move forward with water-wise mitigation action.

Chapter 8. Water Risks and Win-wins for Climate Mitigation

Chapter 8 presents priority water risks that need to be evaluated in climate mitigation plans. Building on Part II of the report, this chapter outlines opportunities to effectively mitigate emissions through measures taken in water and sanitation services (Chapter 4), and the protection, restoration, and management of ecosystems (Chapters 5 and 6). This also includes risks in the development of different renewable energy options, as well as potential implications of land and water degradation to reduce the sequestration potential of ecosystem-based mitigation measures, or that lead to increased emissions of GHGs (Chapter 7). **Essential areas for investment and action are identified that will enable benefits for both water and climate mitigation, critical for sustainable development in the coming decades**. Four leverage points are highlighted to ensure climate mitigation is resilient, robust, and water-wise – including the:

1. **promotion of sustainable low-emission water management**

2. **investment in Nature-based Solutions and healthy ecosystems**

3. **navigating water-wise energy pathways**

4. **accelerating circular solutions and sustainable lifestyles.**

The chapter also touches upon key issues for climate mitigation that are beyond the scope of this report, including industrial processes and design, transport, solid waste management, as well as issues related to diet, sustainable consumption, and behavioural change.

Wetland at Han River Wild Bird Ecological Park, on the outskirts of Gimpo-si, Gyeonggi-do, South Korea. Source: Shutterstock.

Chapter 9. Water & Climate: Achieving climate mitigation through integrated and cross-sectoral approaches

Chapter 9 demonstrates that **integrated approaches, accounting for the interconnections between freshwater and climate mitigation, are necessary to achieve water-wise climate mitigation**. Integrated approaches draw on systems thinking, and unlike siloed approaches, recognize the systemic and connected nature of climate and water. As such, they can assess and address trade-offs, and identify synergies. This chapter provides an overview of some of these approaches, including Integrated Water Resources Management (IWRM), the Water-Energy Food Nexus approach, Source-to-Sea (S2S), the Landscape approach, and Integrated Urban Management, each exemplified through case studies. The chapter notes that successfully delivering integrated approaches require the acknowledgement of complexities across different geographical and management levels, temporal scales, and contexts. Specifically, the chapter argues that governance systems need to be strengthened and enabling conditions created, to deliver water wise climate mitigation through integrated approaches. Enabling conditions include building transparency and data-based decision-making, strengthening capacity through inclusive knowledge systems, innovating finance, and linking governance structures across sectors and scales to create more polycentric and inclusive governance arrangements.

Chapter 10. Concluding remarks: Freshwater - the essential drop to reach net-zero

Looking at Part I, II and III holistically, the chapter attests to the pivotal importance of building strong, polycentric, and inclusive governance systems, which have the capacity to deliver the integrated solutions required for water-wise climate mitigation. Building on that, it is clear that working in silos will fail to deliver the change needed. For our governance systems and national implementation plans to succeed **we need to place water in its rightful place: at the heart of all efforts to adapt to, as well as to mitigate climate change.**

References

IPCC 2022
UNFCCC 2015

CHAPTER 1

Introduction

1.1 Background

Water is at the heart of climate change. As global temperatures rise, the effects of climate change will be felt most strongly through water; translated and intensified through the water cycle, experienced as changing seasonality and precipitation patterns, and manifest as extreme weather events such as droughts and floods (IPCC 2022a). To improve climate resilience, it is essential to address the drivers of climate change (mitigation) and to minimize the damage and exploit the benefits from climate change (adaptation). Since water is at the heart of climate change, it plays a critical role in both mitigation and adaptation. Moreover, successful mitigation and adaptation go hand in hand, and need to be carefully aligned to achieve their goals. Otherwise, mitigation measures that do not take water into account can further endanger water security and prevent mitigation or adaptation efforts from succeeding over the long term.

A strong emphasis has so far been given to the role of freshwater in climate change adaptation. However, freshwater is still an undervalued factor in climate change mitigation despite, as this report shows, its crucial role as an enabler of mitigation measures.

Means for limiting temperature rise are referred to as mitigation measures. In contrast to climate change adaptation measures, which focus on minimizing damages or exploiting benefits from actual or expected climate change, mitigation measures are aimed primarily at addressing the drivers of climate change. Mitigation includes methods to: a) prevent or enhance absorption of greenhouse gas (GHG) emissions (such as fossil fuel substitution and ecosystem protection); b) remove carbon dioxide from the atmosphere (such as ecosystem restoration); and c) mediate the Earth's energy balance without directly interfering with GHG emissions (such as temporarily reducing or offsetting warming through albedo management) (IPCC 2018). Moreover, mitigation measures vary in the degree of technology involved, and the extent to which they harness ecosystem services while simultaneously bringing multiple co-benefits for nature and human well-being. Mitigation measures may also be hybrid nature- and technology-based solutions as well as serving both adaptive and mitigating functions. Sustainable future scenarios, in which Paris Agreement targets are achieved, typically involve all types of mitigation measures.

Considering the urgency of the situation, it is necessary to make use of all available mitigation opportunities. The latest Intergovernmental Panel on Climate Change report concludes that limiting global warming to 1.5°C (above pre-industrial levels) is still possible. However, global GHG emissions must peak before 2025 at the latest, be reduced by 43 per cent below 2019 levels by 2030, by 84 per cent by 2050, and reach net zero by the early 2050s, meaning that the window of opportunity is closing rapidly (IPCC 2022b). To limit global warming to 1.5°C, it is necessary to be not only carbon smart but also water wise.

1.2 Closing the knowledge gap

The lack of attention paid to the connection between water and mitigation stems primarily from a knowledge gap; the interrelations between water cycles, freshwater availability, freshwater limitations, and mitigation of GHG emissions has yet to be clearly articulated and recognized. This report illustrates the urgent need to close this significant knowledge gap.

- **Mitigation does not work without water**. Most mitigation measures needed to reach climate neutrality depend on functional freshwater systems. A great majority of mitigation measures worldwide have a link to water management and water availability in many and diverse ways that must be understood, planned, and accounted for.

- **Water needs to be protected from uninformed mitigation planning**. Most mitigation measures needed to reach climate neutrality also have an impact on freshwater resources. If not planned carefully, negative impacts on freshwater resources might threaten water security, adding additional burdens on adaptation measures or, in some cases, even leading to increased emissions and hindering climate change mitigation. A strong interdependence therefore exists between climate change mitigation, water resources management, and water security.

- **The water sector can actively reduce emissions.** Sustainable water and wastewater management and healthy freshwater ecosystems hold large, untapped GHG mitigation potential and thus, water is a crucial mitigation lever in its own right.

Mammatus clouds gather over parched cropland, Macedonia. Source: Shutterstock.

To raise awareness of the urgent need to recognize the crucial role of freshwater in mitigating climate change and understand the complex interrelations, this report provides a comprehensive scientific assessment attesting to freshwater's essential role in and for climate mitigation. As such, it outlines how freshwater is not only a key component in realizing most mitigation measures, but also that freshwater management can contribute directly to reducing emissions. Reviewing mitigation measures across sectors and biomes, for instance in natural ecosystems, land systems, and energy systems, the report also aims to guide future action. It identifies high-potential water-related mitigation opportunities across the sectors and biomes where water management and wider Nature-based Solutions can contribute to reduced GHG emissions and thus address global warming. It further points out the water-related risks to be avoided in mitigation planning to prevent uninformed and therefore unsustainable GHG mitigation planning from negatively impacting water resources. Water management solutions need to be clearly integrated within broader mitigation strategies at the local, national, regional, and global levels to take advantage of the potential freshwater has to offer. As such, there is a strong argument to make use of substantial co-benefits through integrated approaches, which include climate change mitigation in water resource management, and vice versa. Overall, the report presents both guard rails and leverage points for accelerating water-wise mitigation action and making headway on embedding freshwater perspectives within climate mitigation governance and management.

1.3 Structure of the report

Recognizing the strong interdependence between water and climate mitigation, and the existing knowledge gap, this report provides a comprehensive review of how climate mitigation measures depend substantially on or impact freshwater, and which water and wastewater solutions can contribute to climate change mitigation (Figure 1.1). It is organized in three parts:

- **Part I** provides the background and context within which the report operates. It starts by offering a synthesis of the bio-geophysical processes governing the role of freshwater in climate mitigation, and the human-nature system drivers of climate and water use change (Chapter 2). It then sets out an overview of the governance context of water-related management and climate mitigation measures (Chapter 3).
- **Part II** maps the climate mitigation potential and the associated possibilities and challenges in different biomes and sectors. Specifically, it examines drinking water and sanitation services (Chapter 4), freshwater ecosystems (Chapter 5), land systems (Chapter 6), and energy systems (Chapter 7). Through this analysis, Part II provides an overview of water-related climate change mitigation measures. This includes assessment of synergies and trade-offs between mitigation measures in relation to adaptation measures and other important benefits for human well-being and healthy ecosystems, including provision of food and water; water quality improvement; disaster risk reduction; habitat protection; sediment retention and nutrient cycling; and economic, cultural, and recreational benefits. Thereby, the chapters provide a comprehensive foundation to support in-depth, sector-specific characterization of the role of water in climate mitigation and taking water-informed mitigation action.
- **Part III** builds on the findings presented in Parts I and II, and points to the importance of taking a systems-wide perspective to fully address the complex interrelation between water and mitigation. It identifies risks and win-wins at the intersection between water and climate mitigation (Chapter 8), offers guidance for action to achieve water-wise climate mitigation (Chapter 9) and provides concluding remarks (Chapter 10). Part III explains how identified risks and opportunities can help address multiple challenges as well as the value added to climate mitigation potential by water-wise holistic management through integrated approaches.

1.4 Call to action: Guidance on how to achieve water-informed mitigation action

This report provides useful guidance for decision-makers and practitioners in both public and private sectors as well as climate funding institutions. It underscores the necessity of water-wise policies and climate mitigation measures, and provides guidance on how to achieve

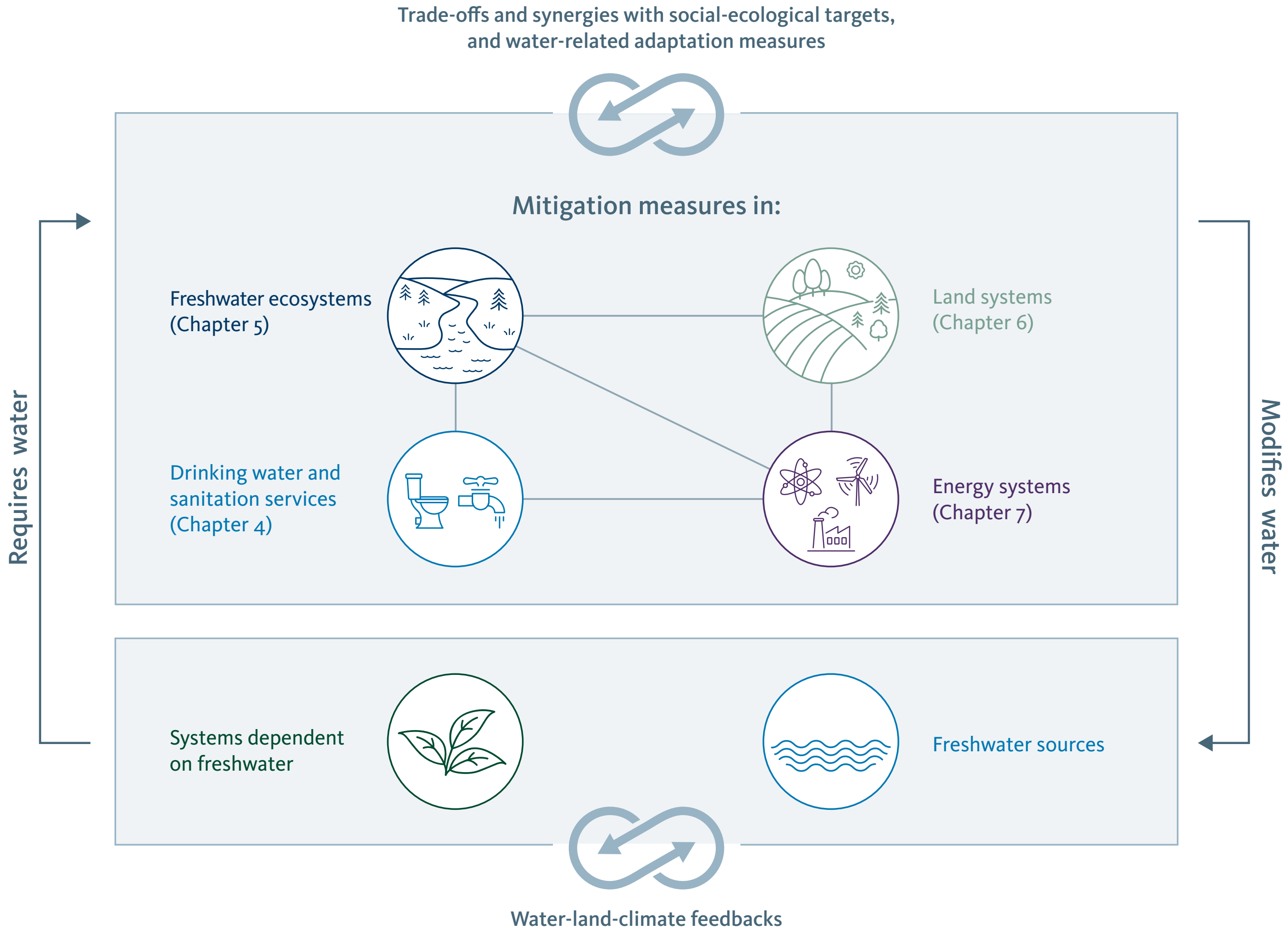


Figure 1.1. This report reviews climate mitigation measures that require and modify freshwater sources and freshwater-dependent ecological and social-ecological systems. Water-land-climate feedbacks mediate those relationships, and multiple freshwater-related synergies and trade-offs exist between climate mitigation and adaptation measures. Source: SIWI.

this integration. It also addresses the climate-, water-, energy-, and land-related communities, providing a solid knowledge base that can be used to build capacity around how water-related activities in these sectors and biomes can contribute further to climate mitigation. This is particularly important as freshwater has the potential to be an enabler of integrated action. However, as demonstrated by this report, there are still substantial data and knowledge gaps in the ways in which water and climate mitigation are linked. The report is therefore also a call to the research community to build a more comprehensive evidence base around these topics.

Finally, the report calls out to funding institutions across the public and private spheres. Making a clear case for the pivotal role of freshwater in mitigating climate change emissions, it is evident that additional water-wise investments will be needed to implement the required measures.

At its core, the report shows that the only way forward is to work together across sectors and institutions to jointly and coherently enhance collaboration and achieve greater impact by acknowledging the role of freshwater as a precondition and leverage point for successful climate mitigation action.

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CHAPTER 2

The role of freshwater in climate mitigation: Biophysical interdependencies

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Chapter 2 Contents

Storm clouds. Source: Josh Sorenson, Unsplash.

Highlights

- The climate system and water cycle are deeply intertwined. Climate mitigation measures needed to achieve the goals of the Paris Agreement fundamentally depend on, and impact, freshwater resources and the water cycle.
- In terms of dependence, a functioning freshwater cycle is crucial to sustain the water security needed for climate mitigation measures to reach their full potential. For example, water stress can hamper energy production from hydropower as well as trigger carbon release from forests, thwarting climate mitigation effects expected from protecting or managing these systems.
- In terms of impact, climate mitigation measures directly modify land, climate, and water quality and quantity, with potentially adverse outcomes. These changes happen on top of already shifting freshwater dynamics, such as droughts and floods caused by ongoing climate change. Combined, they could potentially trigger abrupt and irreversible ecohydrologic regime shifts that may not only affect the implementation and success of mitigation measures but also threaten water security as the foundation of life for humans and ecosystems.
- In the dynamic and hyperconnected Anthropocene era, the relationships between water and climate mitigation can be remote, complex, and non-linear. Holistic systems thinking approaches are thus needed to account for the role of freshwater in climate mitigation to enable decisive and sustainable climate action.

2.1 Introduction

The water cycle is a crucial part of the planetary system. The water cycle supports the living world by enabling photosynthesis, transporting nutrients, and regulating temperature and wind patterns. The Earth systems – land, ocean, atmosphere, and ice – are fundamentally connected and regulated by the freshwater cycle (Gleeson et al. 2020). At the same time, water is very sensitive to climate change and land-use change, which result in altered water flows and availability. This means freshwater stocks and flows are both driving and being impacted by changes in the Earth system, including the climate. In the policy and governance realm of climate change, however, freshwater is mentioned mainly as an interface for the impacts of climate change in the context of climate adaptation (IPCC 2022a; 2022b). However, the role of water as a driver in the climate system, and crucial precondition and lever to climate mitigation, is frequently overlooked (IPCC 2022b). Understanding the role of water in climate mitigation creates a need to look at water in all its guises. While management of surface water resources tends to be in focus, invisible water in the soil and atmosphere gets relatively little attention (Keys et al. 2017; Rockström et al. 2010; Wierik et al. 2020).

This chapter explains – from a biophysical Earth system perspective – why freshwater cycle dynamics should be accounted for in climate mitigation. First, it provides an introductory explanation of the role of the freshwater cycle in the Earth system based on current scientific understanding (Box 2.1). Then, it presents the climate mitigation measures in focus in this report, covering interventions in land-based and freshwater ecosystems; the energy sector; and water, sanitation, and hygiene (WASH) sector (Section 2.2). Based on Earth system knowledge, we unpack how key mitigation measures impact and depend on freshwater and freshwater-dependent ecosystems (Section 2.3). Finally, this chapter describes why rapid and water-smart climate mitigation is important for avoiding potentially persistent and abrupt shifts in social, hydrological, and ecological systems (Section 2.4).

Box 2.1. The global water cycle as the bloodstream of the Earth system

Freshwater is in constant movement regulated by land-based and freshwater ecosystems, atmospheric processes, and anthropogenic activities. Water from the oceans evaporates to supply the atmosphere with water vapour, form clouds and precipitate as rain or snow. Precipitation over land may infiltrate the ground to provide soil moisture, recharge groundwater stocks, and create surface runoff that flows to rivers, lakes, wetlands, and reservoirs.

The continuous movement of freshwater is critical to all terrestrial lifeforms, including the enabling of photosynthesis and biomass production. At the same time, freshwater flows occur thanks to vegetation activities that pump soil moisture into the atmosphere, thereby creating enormous water flows despite relatively small freshwater stocks in the atmosphere, soil, and other liquid water bodies (Figure 2.1). For example, atmospheric moisture volume at any given time is on average around 13,000 cubic kilometres (km³), but serves the transport of around 470,000 km³/year of oceanic evaporation, 424,000 km³/year of oceanic precipitation, 46,000 km³/year water vapour transport from ocean to land, 120,000 km³/year terrestrial precipitation over land, and 74,000 km³/year total terrestrial evaporation (Douville et al. 2021; IPCC 2022c). Water in rivers, lakes, and groundwater is referred to as blue water, whereas plant-available water in soil is referred to as green water. Blue water is used for irrigation, hydropower, and societal water use, and green water is critical for terrestrial ecosystems and most of the world's agriculture and food production (Falkenmark and Rockström 2006).

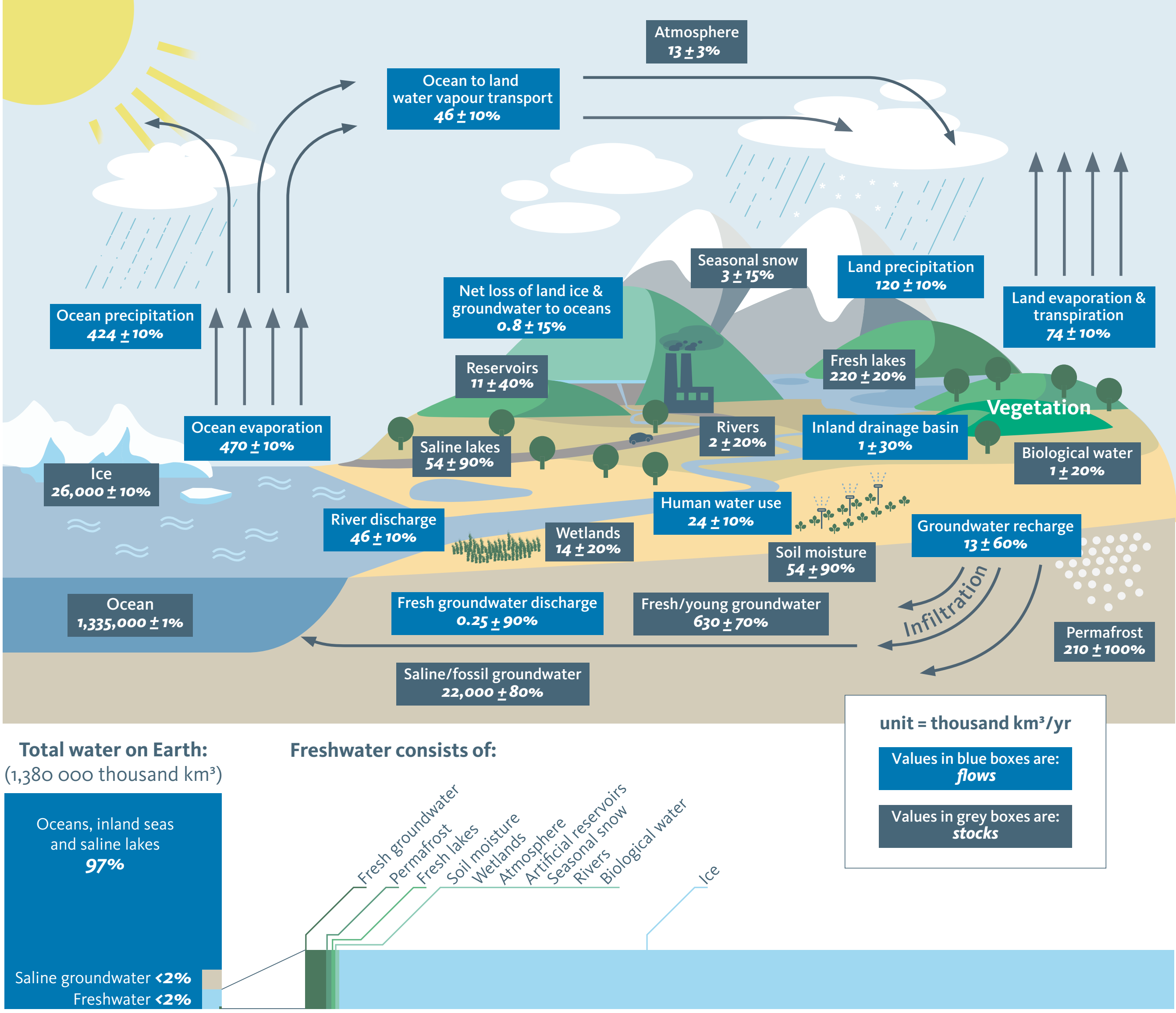

Figure 2.1. The global water cycle with estimates of water flows and stocks. Numbers from IPCC AR6 Chapter 8 Fig 8.1. https://www.ipcc.ch/report/ar6/wg1/figures/chapter-8. Graphic adapted from GIZ (2020), with quantitative estimates synthesized by Douville et al (2021).

Box 2.1. Cont.

Freshwater vapour feedbacks connect upwind evaporation to downwind rainfall, which means that land use in upwind areas has implications for downwind water resources, and potentially further cascading impacts on downwind ecosystems and the water cycle. On a global average, 60 per cent of land evaporation (of which 60 per cent comes from vegetation transpiration and the rest from evaporation from soil and vegetation canopies) recycles and contributes to precipitation over land again; and 40 per cent of land precipitation originates from land evaporation. In some areas, such as in large parts of Eurasia, southern South America, and West and Central Africa, the vast majority of land precipitation has a terrestrial origin and thus depends heavily on terrestrial vegetation activities for producing the moisture that supplies its rainfall (Keys et al. 2016; van der Ent et al. 2010). The upwind lands that supply moisture for an area of interest can be referred to as 'precipitationshed' (Keys et al. 2012). Freshwater systems thus do not respect administrative boundaries and extend far beyond the catchment or river basin scale.

2.2 Bloodstream of the Earth: The fundamental functions of freshwater in the Earth system

Freshwater is crucial to the functioning of the entire Earth system. The holistic systems perspective taken in this report is grounded in the scientific understanding that the freshwater cycle is an integral part of the Earth system, which comprises the land, the ocean, the atmosphere, and ice and glaciers (Box 2.1).

Freshwater serves four major Earth system functions: storage, transport, hydro-ecological regulation, and hydro-climatic regulation (Figure 2.2). Of all water on Earth, only 1 per cent of freshwater is available to ecosystems and societies, with the rest stored in oceans (97 per cent) or bound in ice and deep groundwater. Both the available and unavailable freshwater storage is critical, for example for regulating sea levels, sustaining base flows to rivers, and buffering fluctuations in water availability. Importantly, driven by the sun, freshwater is in constant movement, allowing its role in the Earth system and for climate mitigation to go far beyond its relevance in terms of availability to ecosystems and societies. As an agent of transport, freshwater moves sediments, nutrients, and carbon, thereby shaping landscapes, nutrient cycles, and carbon cycles. Moreover, the spatial and temporal distribution and movement of freshwater are essential for supporting and regulating ecological functions on land and water. Freshwater directly supports land-based life by enabling physiological processes such as photosynthesis, and aquatic life by providing freshwater habitats such as rivers, lakes, wetlands, and coastal systems. Finally, freshwater regulates climate across different scales by modifying the energy balance,[1] since moisture content regulates cloud formation,[2] surface temperature, the land-ocean temperature gradient, and atmospheric turbulence and circulation. For example, droughts can drive fires, irrigation can delay monsoon onset, and high humidity can lead to deadly heatwaves that are beyond human physiological tolerance (Russo et al. 2017).

Freshwater also serves its hydro-climatic function through intertwinements with the global carbon and methane budgets; i.e., the two types of greenhouse gases (GHG) with the largest influence on anthropogenic global warming. Carbon dioxide can persist in the atmosphere for thousands of years, and emissions therefore accumulate. Fossil fuel production and use is the largest carbon emitter by far, followed by land-use change. Oceans, soils, and vegetation are currently the largest carbon sinks, and human removal of carbon from the atmosphere in the future will be necessary to limit climate change to 1.5 to 2°C (above pre-industrial levels).

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[1] The Earth maintains a stable temperature over time if the net incoming energy from the sun is balanced by the net outgoing energy from the Earth. The incoming energy from the sun is unevenly distributed, and the regional temperature and climate depends on energy redistribution across the Earth system.

[2] Clouds block sunlight and help cool the planet as a whole, although clouds can also trap more heat than they reflect. Whether in the future clouds will contribute to warming or cooling at the global and regional scales is an active area of research.

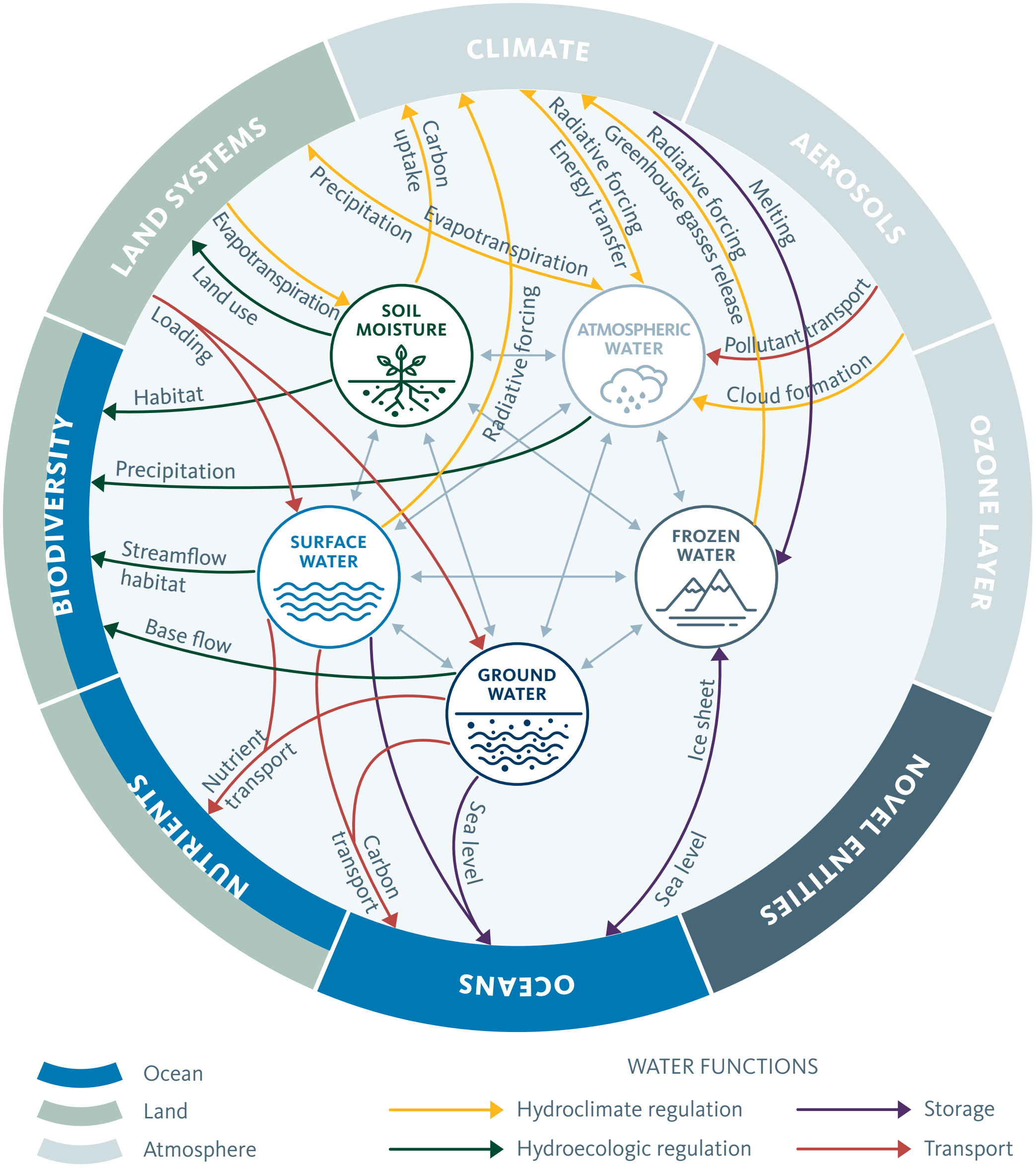

Figure 2.2. Four core Earth system functions of freshwater. The five major stores of water (soil moisture, atmospheric water, frozen water, groundwater, and surface water) interact substantially with all components of the Earth system. Source: Gleeson et al. (2020).

Methane is ~30 times more potent than carbon in a 100 years perspective, but it is short-lived in the atmosphere (~12 years). Agriculture, wetlands, and different forms of waste are the largest methane emitters, followed by fossil production and use (Figure 2.3). Worryingly, warmer water is more prone to emit methane, while wildfires and biomass burning consume the hydroxyl radicals that are necessary for removing methane from the atmosphere (Cheng and Redfern 2022). Nitrous oxide is another potent GHG that originates from agricultural fertilizers, wastewater, and deforestation, as well as from fossil fuel use and industries (Tian et al. 2020). It remains in the atmosphere for 109 years, and its warming potential is 273 times than carbon dioxide over a 100 years period. Atmospheric concentrations of both methane and nitrous oxide have grown beyond expectations in recent years, underscoring the urgency of addressing these emissions. In addition, vast amounts of GHGs are stored latently in soil, biomass, and oceans. These stores can be many times larger than the total fossil fuel reserves on Earth and need to remain undisturbed (Figure 2.3).

For resilience and sustainability, freshwater thus plays (sometimes simultaneously) three different roles: a) a **provider of resilience**; i.e., by maintaining system functions, such as the upholding of habitats that continue to store and sequester land carbon; b) a **victim of change**; i.e., as freshwater flows and stocks are modified by human pressures or modifications such as forestation impacts on river flows; and c) a **driver of change**; i.e., as freshwater change generates impacts, such as drought impacts on fire risks (Falkenmark et al. 2019; Rockström et al. 2014).

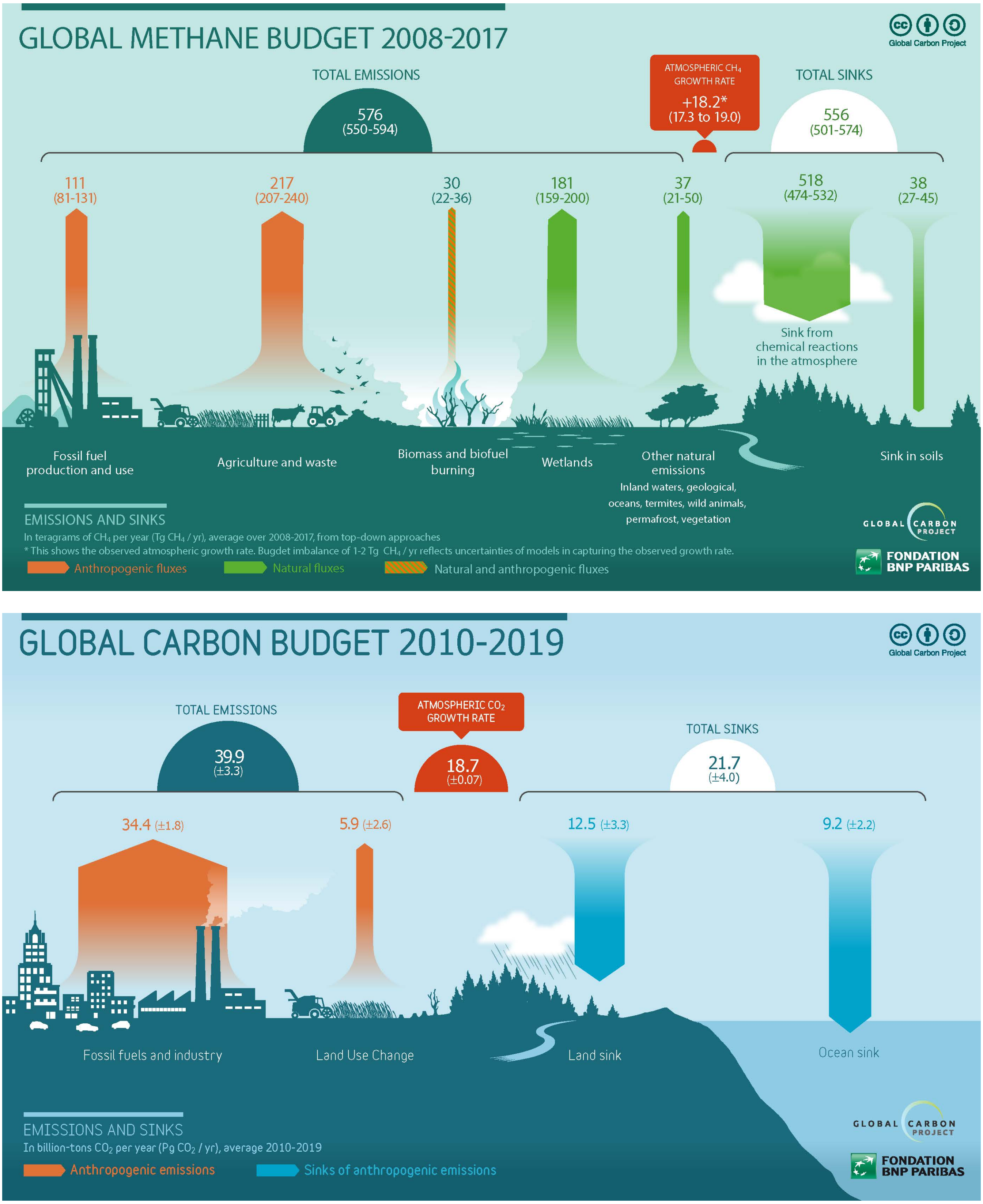

Figure 2.3. Global carbon and methane budgets: a) Global methane budget, average 2008–2017. Source: Saunois et al. (2020); b) Global carbon budget, 2021. Source: Friedlingstein et al. (2022). Graphics courtesy of the Global Carbon Atlas (www.globalcarbonatlas.org).

Together, the four Earth system functions and the three roles of freshwater are dynamically and inseparably interlinked and shape the ways mitigation measures depend on and impact freshwater and freshwater-dependent ecosystems. Thus, water cannot be taken out of the equation when saving the functioning of the Earth system from climate change.

2.3 Introduction to key water-related mitigation measures

To prevent further damage and reach the goal of the Paris Agreement to limit global warming to 1.5 to 2°C above pre-industrial levels (1850–1900), all sectors urgently need to lower their emissions following a holistic approach. The window of opportunity to achieve the Paris Agreement is closing, as global carbon dioxide (CO_2) emissions now need to peak before 2025 and reach net zero by the early 2050s (IPCC 2022b). Otherwise, climate risks to societies and ecosystems will increase with global warming and reach dangerous levels, resulting in water and food insecurity, extreme weather events (such as heatwaves, droughts, fires, storms, flooding), ecosystem regime shifts,[3] sea-level rise, ill health, economic damage, and more (IPCC 2022a). And yet, we are not on track. Current anthropogenic-driven climate change has already led to a 1.1°C warmer world, and without deep reductions in GHG emissions, global warming of 1.5°C and 2°C will be exceeded during the 21st century (IPCC 2022b).

Scenarios that comply with the Paris Agreement temperature target rely on the Earth system's capability to continue to store carbon, which may be compromised due to adverse climate change impacts (Figure 2.4). Various scenarios and pathways to rapid decarbonization exist and include both considerable reductions in human GHG emissions and removal of CO_2[4] from the atmosphere by locking it in human and biosphere carbon sinks. Human carbon emissions are caused by combustion of fossil fuels (coal, oil, and gas) and land-use change, whereas biosphere carbon sinks include uptake of carbon in soils, and dead and living matter in terrestrial and oceanic systems. Human carbon sinks are needed to achieve net zero and refer to uptake and durable storage of carbon in land, oceans, geological formations, or products. Human carbon sink methods that rely on land and freshwater systems include afforestation, reforestation, improved forest

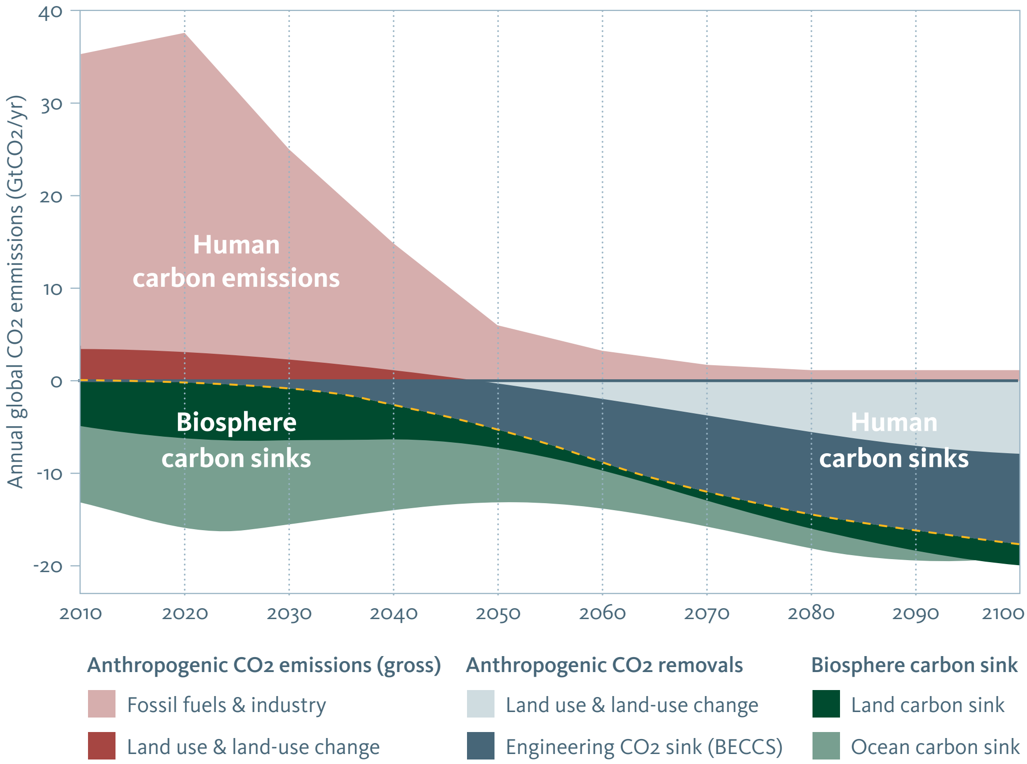

Figure 2.4. Sustainable future scenarios, in which Paris Agreement targets are achieved, typically involve mitigation measures that: a) rapidly cut human GHG emissions; b) maintain the biosphere's capacity to store and sequester carbon; and c) remove carbon from the atmosphere. The figure illustrates a roadmap for rapid decarbonization that meets the Paris Agreement by bending the carbon emissions curve by 2020, reaching net zero by 2050 and increasing human carbon removal such as carbon sinks from BECCS. Source: re-printed with permission from Folke et al. (2021); modified after Rockström et al. (2017).

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[3] Large, abrupt, and persistent changes in the structure and function of ecosystems, which are difficult or impossible to reverse.

[4] Removal of methane and nitrous oxides are being hypothetically explored in the scientific literature (Lackner 2020; Jackson et al. 2019).

management, agroforestry, soil carbon sequestration, peatland restoration, and 'blue carbon'[5] management. Many of these human carbon sinks can contribute simultaneously towards sustainability in several aspects. Others, however, such as afforestation and bioenergy with carbon capture and storage (BECCS),[6] may imply undesirable risks and trade-offs with regards to water and food security, biodiversity, and social systems that need to be considered (IPCC 2022b; also see Chapters 6 and 7).

This report focuses on both human and biosphere mitigation measures that interact considerably with the freshwater cycle and freshwater-based ecosystem processes. This includes mitigation in the WASH sector, freshwater ecosystems (such as wetlands, rivers, etc.), terrestrial systems (such as forest/forestry, grassland/rangeland, and croplands), and the energy production sector, which all crucially depend on or impact water. Mitigation measures with high mitigation potential are also found in the transport, waste, industrial, and buildings sectors, but are not addressed here since the interdependencies with the freshwater cycle are mostly indirect. All in all, the water-interdependent mitigation measures addressed in this report encompass most of the total mitigation potential (Figure 2.5).

2.4 Towards net zero: Why key climate mitigation measures depend on and impact freshwater

The freshwater cycle has been described as the bloodstream of the biosphere and the Earth system (Ripl 2003), meaning that climate mitigation measures and the water cycle are inseparable from the Earth's climate and biosphere processes. As such, all climate mitigation measures inevitably depend on or impact freshwater cycling. Climate mitigation measures (for the purpose of limiting global temperature rise) intervene in land-based systems, freshwater systems, and technological systems, which all depend on the availability of green and blue water of good quality. Conversely, the failure or success of climate mitigation efforts directly impacts how climate change affects the water cycle as well as the effectiveness of climate mitigation measures.

To start with, absent or insufficient mitigation measures are likely to lead to more severe climate change, and thereby to potential shifts in hydro-climatic regimes (Dai 2021; Destouni et al. 2012; Piemontese et al. 2019) and abrupt changes in the water cycle (Huntington

Early morning evaporation from a freshwater lake, Sweden. Source: Shutterstock.

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[5] Carbon storage in coastal and marine ecosystems, i.e., mangroves, tidal marshes, and seagrasses.

[6] BECCS is a negative emission technology that involves harvesting biomass for energy production and storing carbon in geologic formations or land (see Chapter 7).

Many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030. Relative potentials and costs will vary across countries and in the longer term compared to 2030.

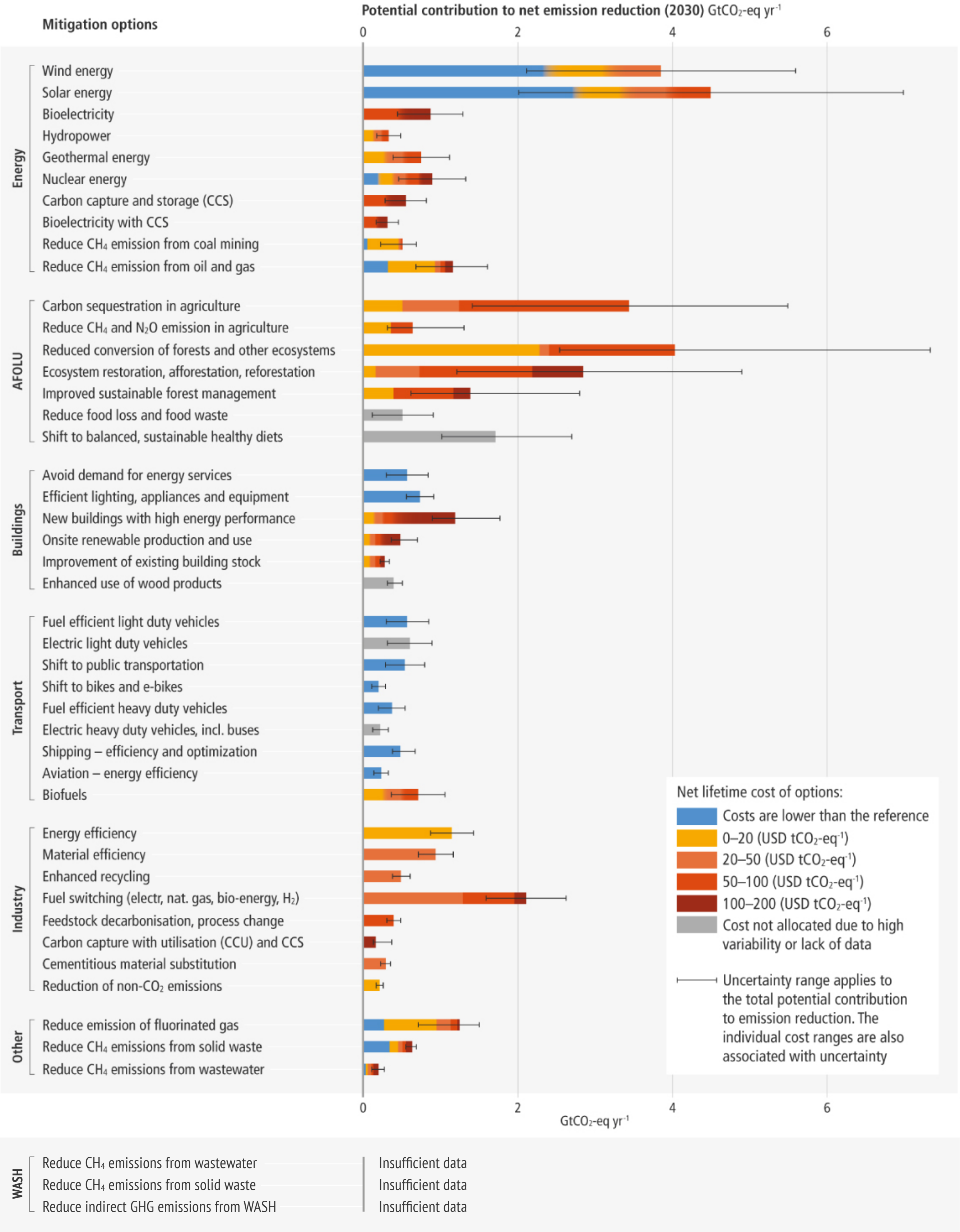

Figure 2.5. Mitigation measures across sectors and their mitigation potential to reduce net emissions by 2030. Source: IPCC Sixth Assessment Report, https://www.ipcc.ch/report/ar6/wg3/figures/summary-for-policymakers/figure-spm-7/. The WASH section is based on the findings in Chapter 4 of this report.

2006; Zhang et al. 2019). Many regions are swiftly becoming either wetter or drier, which alters ecological and biogeochemical functions and processes. The shifting hydroclimate and water cycle intensification lead to increasingly frequent and severe water-related extremes, including fires, droughts, heatwaves, storms, extreme precipitation events, and subsequent risks of erosion, flooding, and landslides (IPCC 2022b). With increasing frequency of extreme events, individual risks are more prone to aggregate into compound risks (which result from multiple simultaneous and interacting climate and non-climate risks), such as food insecurity aggravated by concurrent droughts, heatwaves, and conflicts (IPCC 2022c; Zscheischler et al. 2018).

The speed of change can exceed the capacity of ecosystems to adapt and compromises their capacity to retain their functions and structures under external disturbances. Limits to adaptation are already being felt and will increase with further warming (IPCC 2022c). Human impacts on climate, land, and water together increase the risk of abrupt ecological and social-ecological change that are difficult or impossible to reverse (i.e., tipping points, see Figure 2.6). Such regional water risks arising primarily from global change include glacier melt, sea-level rise, salt-water intrusion, and drastic rainfall regime change. Mismanagement of land and water further contribute to the risk of gradual collapse or irreversible tipping. Examples include land degradation (e.g., loss of infiltration capacity further contributes to drying soils), salinization (e.g., if agricultural land is irrigated with salty water), Amazon forest dieback (e.g., forest loss leads to reduced evapotranspiration and regional precipitation), and groundwater depletion and surface water depletion (e.g., river water is consumed before reaching the ocean). This means that the necessary large-scale and rapid roll-out of climate change mitigation measures, at the same time, must avoid contributing to mismanagement and resilience loss in land-based and freshwater systems.

Unmitigated climate change impacts on soil moisture will compromise the effectiveness of many land-based mitigation measures. Mitigation measures dependent on the ability of ecosystems to store and sequester carbon are directly impacted by changes in green water fluxes and stores. For example, climate change induced decreases in soil moisture often limit the capability of plants to grow and sequester carbon both below and above ground (Green et al. 2019; Samaniego et al. 2018). As plants wither and wetlands dry up, they revert from being a carbon sink to become a carbon source. Instead of absorbing CO_2 emissions, they release stored GHGs to the atmosphere, accelerating climate change. This is already happening in the tropical rainforests (Hubau et al. 2020). There are concerns that a global tipping point of carbon sink-to-source reversal will occur by the middle of this century under severe climate change (RCP8.5)[7] (Green et al., 2019). An increasing concentration of CO_2 in the atmosphere initially enables more water-efficient photosynthesis (i.e., CO_2 fertilization), thus bolstering vegetation growth and increasing carbon uptake. However, eventually, the CO_2 fertilization effect will saturate (Green et al. 2019) due to such limits as the maximum ecosystem photosynthesis rate or because of water limitations, nutrient limitations, and other constraining factors (Wieder et al. 2015). Increased wetting caused by thawing permafrost can cause increased CO_2 and methane release (Schaphoff et al. 2013; Turetsky et al. 2020). The success of mitigation measures that are aimed at the protection and restoration of terrestrial systems for carbon storage and uptake thus depend on the future severity of (incompletely mitigated) climate change.

Similarly, unmitigated climate change impacts on blue water can be expected to lower the mitigation potential of measures aimed at the protection and restoration of aquatic systems. For example, regional declines in groundwater recharge (Portmann et al. 2013) may limit water availability for delivering groundwater-dependent mitigation measures such as ecosystem restoration, reforestation, electricity production, and mining for minerals, which are needed to produce renewable infrastructure. Increased flooding risks, associated with precipitation extremes and glacial melt under climate change (Merz et al. 2021), present further risks to downstream aquatic ecosystems, hydropower dams, and other water infrastructure. Climate change increases the fraction of the world's population exposed to water scarcity (Gerten et al. 2013; Heinke et al. 2019) (Figure 2.7), which will require resilient and efficient water infrastructures for supplying water to households and industries. The capacity of coastal and marine systems to sequester and store carbon can be further compromised by rising sea level as well as increasing incidence of extreme events such as marine heatwaves and storms (Macreadie et al. 2019).

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[7] This high-emissions Intergovernmental Panel on Climate Change scenario is frequently referred to as 'business as usual', suggesting that is a likely outcome if society does not make concerted efforts to cut GHG emissions.

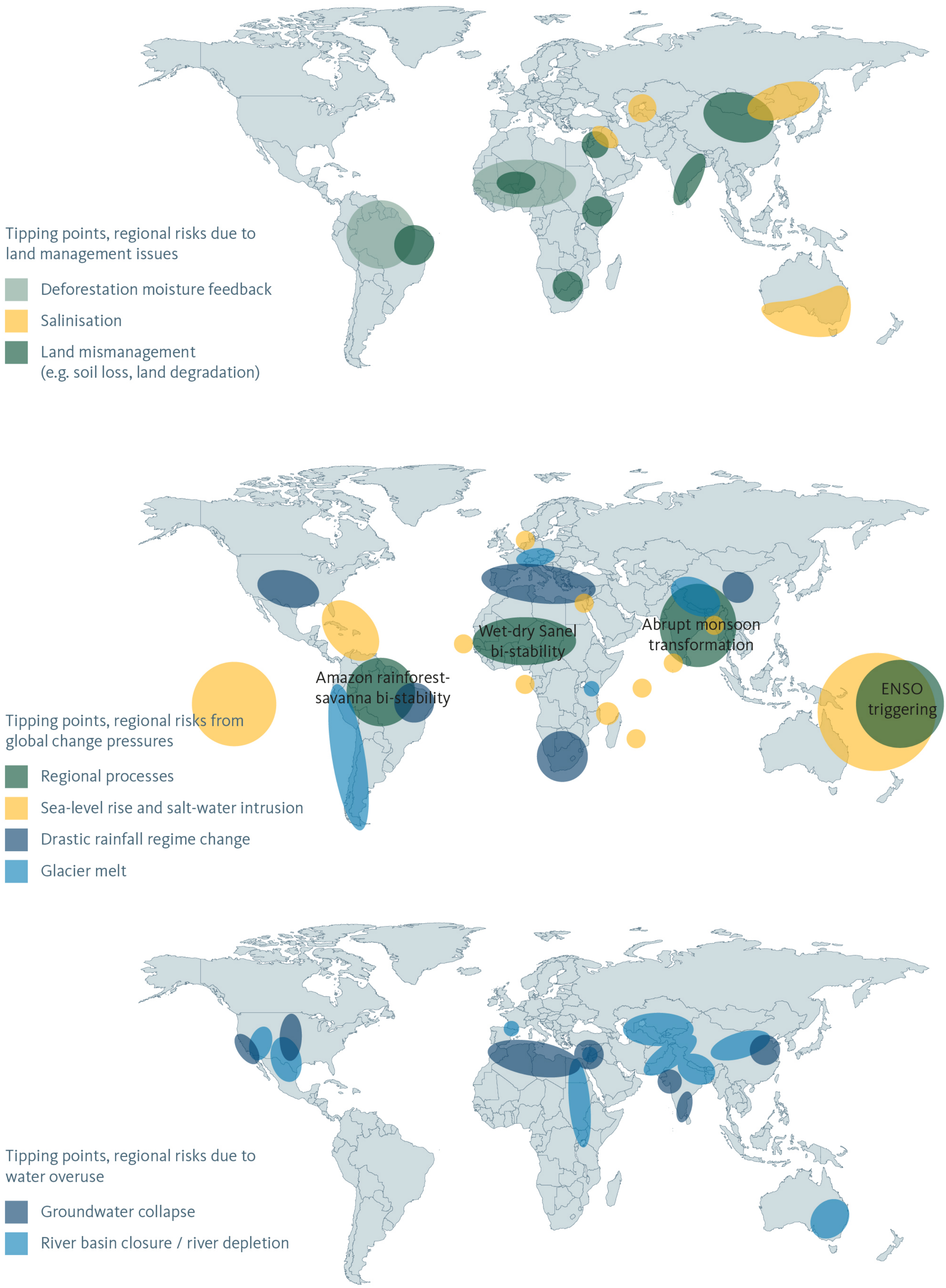

Figure 2.6. Water-related tipping points in the Earth system. In addition, permafrost thawing associated with local abrupt shifts can be expected under climate change. Source: Rockström et al. (2014); Schaphoff et al. (2013); Turetsky et al. (2020).

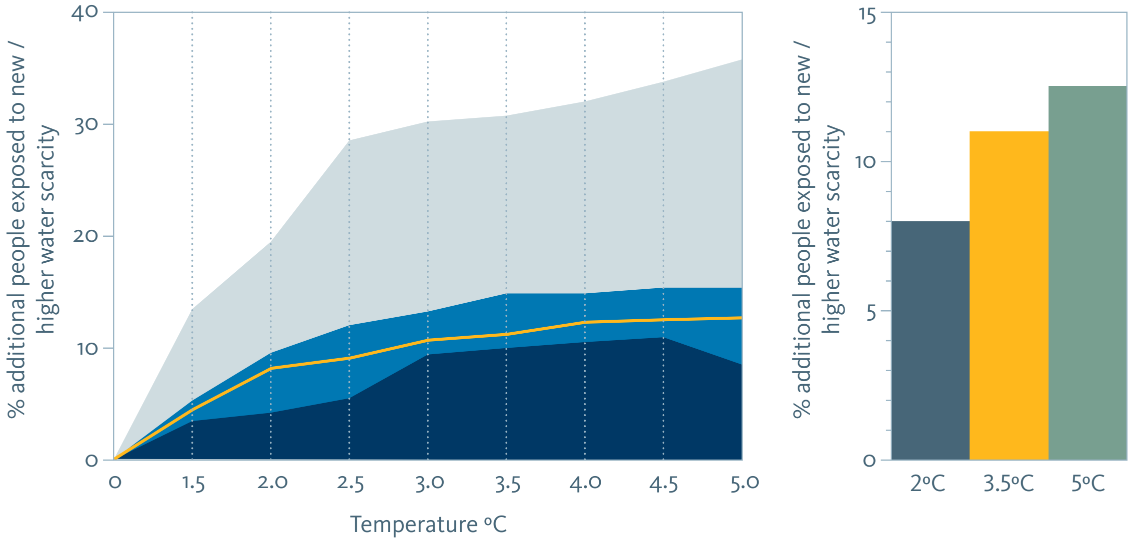

Figure 2.7. With every degree of global warming, more people will be exposed to water scarcity. Source: Heinke et al. (2019).

A rapid rollout of mitigation measures is, however, not risk free for water and needs to be carried out carefully to prevent unintentional harm. The way that mitigation measures directly affect and depend on freshwater vary in land-based ecological and production systems, freshwater ecological and production systems, and technological systems (Figure 2.8).

1. Mitigation measures in land-based ecological and production systems refer to climate actions in forests, agriculture, grasslands, and rangelands. They aim to lock carbon in those land systems instead of releasing it into the atmosphere by increasing land carbon sequestration and maintaining land carbon stocks. At the same time, most interventions on land lead to changes in vegetation types and management methods, thereby resulting in changes in surface reflection and evaporation, which affect local temperatures. Increased carbon sequestration can be achieved through expanded above- and below-ground biomass, such as by reforestation, afforestation, and forest management. However, land-based ecosystems need to remain intact to harness their mitigation potential. Ecosystem health in turn depends on water security; carbon stocks in the soils and biomass of ecosystems need to be maintained to have a climate mitigating effect in the long term. Yet forests and grasslands cannot thrive without water. In addition, the longevity of these living carbon stocks is subject to extreme events and climate change. For example, drought may facilitate wildfires, which cause vegetation mortality and prevent growth. Hence, it directly obstructs carbon sequestration in land systems and even releases land carbon stocks to the atmosphere (Wen et al. 2020). Changes in the carbon balance, however, are only one of many biophysical aspects of mitigation interventions in land systems. An assessment of the overall effect on surface temperatures needs to also include effects of land conversion/management on surface albedo[8] and non-radiative forcing.[9] This refers to local cooling through evaporation and turbulence increase. For example, conversion of grassland to coniferous tree cover in boreal areas may lead to an increase in the Earth's energy balance (Bala et al., 2007; Bonan, 2008; Swann et al., 2010), but simultaneously lower local temperatures (Bright et al. 2017), which can be very important for preventing fires, vegetation mortality, and species loss.

2. Freshwater ecological and production systems encompass wetlands, lakes, rivers, reservoirs, groundwater, and freshwater-dependent coastal and marine systems. They are dependent on water security and critically relevant to mitigation measures by, among others, storing and absorbing GHGs (CO_2, methane, and nitrous oxide, see Chapter 5) and enabling

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[8] Albedo refers to the fraction of radiation that is reflected by a surface. Dense vegetation types, such as forests, typically have a lower albedo than grasslands, croplands, and deserts.

[9] Non-radiative forcing refers to a change to the partitioning and distribution of energy that can affect temperature, without affecting the overall radiative balance of the Earth. Non-radiative forcing includes changes in evaporation (i.e., heat fluxes that cause evaporation do not contribute to surface temperature change) and surface roughness (i.e., land with high vegetation cover has higher surface roughness than barren landscapes). For example, tropical deforestation increases temperature through both types of non-radiative forcing: non-forests have lower surface roughness, thereby lower atmospheric turbulence, which prevents warm air from leaving the surface area; and non-forests also evaporate less, thereby lower evaporative cooling effects, which increases surface temperatures (Davin and de Noblet-Ducoudré 2010).

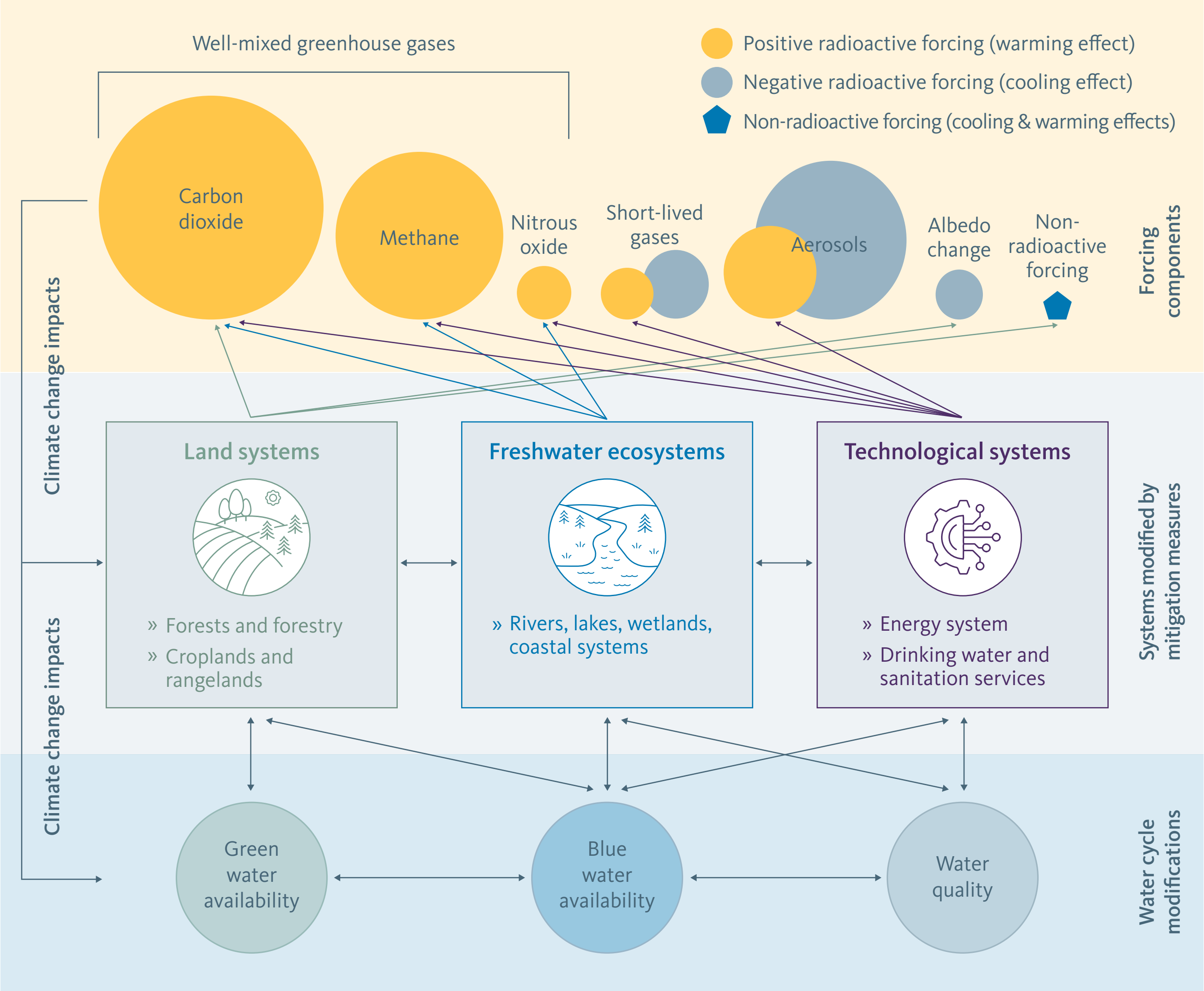

Figure 2.8. Overview of the key relationships between water-related mitigation measures and climate forcings. The size of the circles represents rough approximates of the magnitude of the forcing changes over the period 1750–2011 and includes all changes (i.e., not only from the terrestrial and aquatic systems or fossil energy sources). Source: Stockholm International Water Institute.

renewable and low-emission energy generation (Chapter 7). The densest and most long-term carbon stocks are found in natural aquatic systems. However, they are at risk of reverting from net sinks to net sources as a result of drainage, pollution, global warming, and other human pressures. For example, if a peatland ecosystem is destroyed or degraded, the carbon it stores is released into the atmosphere. This is particularly concerning because peatlands store twice as much carbon as the world's forests (see Chapter 5) and peatland degradation currently represents up to 5 per cent of human emissions (HLPW 2018). In many regions, the impact of drying and wetting on climate change further depends on the balance between aerobic emissions of CO_2 (long-lived in the atmosphere) and anaerobic emissions of methane (~30 times larger warming potential over 100 years). Yet, for example, to replace fossil-fuel-based energy sources, future zero emission scenarios typically assume dramatic expansions of hydropower (e.g., 60 per cent increase in the next 30 years) (IRENA 2020) with potentially large impacts on fish migration, ecosystem health, and livelihoods (see Chapter 7). Thus, the overall potential of aquatic systems to contribute to climate change mitigation depends on safeguarding the capacity of these systems to act as persistent GHG sinks, while planning the provision of renewable energy.

3. Mitigation measures in freshwater-related technological systems addressed in this report primarily concern the WASH sector and the energy sector. The WASH sector uses 4 per cent of the global water supply with considerable opportunities for increases in energy efficiency. In addition, reductions can be achieved in the methane and nitrous oxide emissions from water and wastewater treatment, desalination, and water infrastructures (Chapter 4). A rapid transition of global energy production from fossil to renewable and low-emission energy sources is fundamentally interdependent on freshwater. Among others, hydropower and bioenergy are the renewable energy sources most directly dependent on freshwater for generating energy directly by moving turbines and in biomass production respectively. Thermal electricity generation from nuclear, concentrated solar, and geothermal energy can require large volumes of water for their operations (cleaning and cooling) and discharged water can impact temperature and environmental health in freshwater systems. Taken together, decarbonization of the energy sector requires water security due to considerable water use for cooling, cleaning, biomass production, and the energy generation itself (Chapter 7).

2.5 Carbon smart and water wise: How to achieve sustainable mitigation action

We need to prevent uninformed water mitigation planning from threatening freshwater resources and ecosystems to safeguard mitigation potentials. The circularity between mitigation measures and freshwater systems must be acknowledged and taken into account during planning.

Mitigation measures that modify freshwater and freshwater-dependent systems can similarly have indirect impacts on subsequent mitigation potential, creating both risks and win-win situations. Water risks can be expected, for example, with hydropower, which can help reduce reliance on fossil fuel energy sources and reduce emissions, but might simultaneously negatively impact the ecological functioning and carbon sequestration capacity of local aquatic systems (Moran et al. 2018). Moreover, irrigation-dependent plantations for measures such as BECCS (Stenzel et al. 2021) could unintentionally deplete local water resources (see Chapter 7), with detriments to the original ecological and carbon sequestering functioning of the impacted ecosystems. Win-wins are, fortunately, also numerous. For instance, better wastewater treatment reduces the GHG emissions from untreated wastewater, improves surface water and groundwater quality, and provides renewable energy through biogas (Macreadie et al. 2019). Restoration of forests and wetlands also has a high potential to serve social, ecological, and climate benefits all at once (Di Sacco et al. 2021). In many cases, the risks and win-wins are complex and depend on both context and the water-wise execution/operation of the planned and proposed mitigation measures.

Overall, freshwater is crucial to the functioning of the entire Earth system and the fundamental underpinning of societies, livelihoods, and the world's economy (Daily 1997; Dasgupta 2021). Mitigation measures in the WASH sector, energy sector, and involving terrestrial and aquatic systems inevitably depend on and impact freshwater systems. Freshwater availability impacts ecosystems' ability to absorb and store carbon, methane, and nitrous oxide; freshwater is used for energy generation and in technological processes within renewable and low-emission energy production. Climate change, however, is already negatively impacting freshwater availability and quality. Slow or insufficient climate mitigation will lead to extreme events, such as droughts, fires, and floods, as well as to hydroclimatic shifts and abrupt changes in ecosystems that will disrupt the freshwater functions that critically support and enable a large range of nature-based and technological mitigation measures.

Therefore, mitigation measures need to be rolled out rapidly while at the same time restoring and limiting negative impacts on freshwater resources and freshwater-dependent systems. Time is a critical factor, as rapid implementation of mitigation measures that limit climate change is also likely to benefit the effectiveness of freshwater-dependent mitigation measures. It is critical to restore and limit negative impacts on ecosystem functioning because ecosystems' capacity to store and sequester carbon is intimately reliant on ecosystem health. The precarious conditions of the Earth system, with transgressions in six out of nine planetary boundaries – including that of freshwater change (Wang-Erlandsson et al., 2022) – further motivates ecosystem-friendly mitigation measures and stresses the need for caution concerning mitigation measures that carry freshwater risks.

Rapid and water-smart mitigation measures are needed to harness the potential of freshwater ecosystems and avoid jeopardizing health, water, food, and energy security, which form the foundations of societies.

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CHAPTER 3

Governance context of water-related climate mitigation measures

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Chapter 3 Contents

Misty morning at the Upo Wetland near Changnyeong-gun, South Korea. Source: Shutterstock.

Highlights

- Climate change, biodiversity, land, water, and sustainable development are governed by an array of global governance frameworks and national instruments, including:
    - *Climate change:* United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, the 2015 Paris Agreement and its associated Nationally Determined Contributions (NDCs), National Adaptation Plans (NAPs), and Long-Term Strategies (LTSs).
    - *Biodiversity and land governance:* The Convention on Biological Diversity (CBD) and its associated National Biodiversity Strategies and Action Plans (NBSAPs) and the United Nations Convention to Combat Desertification (UNCCD) and its associated National Action Programmes.
    - *Water:* The Ramsar Convention, the United Nations Watercourses Convention, Integrated Water Resources Management (IWRM), and the United Nations International Decade for Action: Water for Sustainable Development.
    - *Sustainable development:* The 2030 Agenda for Sustainable Development.
- Various financing mechanisms and instruments are also available to further implementation, including:
    - Global Environment Facility (GEF), Green Climate Fund (GCF), and Clean Development Mechanism (CDM).
    - Market-based mechanisms such as Payment for Ecosystem Services (PES), Water Funds, and water stewardship approaches.
    - Innovative financial mechanisms such as blended finance, guarantees, and bonds (green, blue, sustainability).
- Because interlinked issues such as climate, water, land, and sustainable development are conceptualized, governed, and financed separately, siloed approaches become the norm. By extension, this creates barriers to the achievement of climate mitigation as leverage points are not capitalized on, and risks are not accounted for.
- Integrated approaches are needed to overcome these barriers. To better leverage connections, it is necessary to understand and articulate the synergies among different issues more clearly and create links between different governance structures to facilitate integrated approaches that can capitalize on these synergies. Failing to do so is a missed opportunity for climate change mitigation, which we cannot afford.

3.1 Introduction

To deliver on climate mitigation at the scale and speed needed, water must be mainstreamed into the climate governance process. As chapters 4 to 7 in Part II demonstrate, key climate change mitigation measures depend on, and impact water. Water also holds significant mitigation potential in its own right. However, the mainstreaming of water into climate governance processes such as the NDCs has not occurred to the extent needed. While climate adaptation efforts account to a large degree for water through, for example, NAPs, governance efforts that systematically integrate water considerations into climate mitigation policies, investments, and practice are still missing (Brouwer et al. 2013; Cook et al. 2010; Matthews et al. 2019).

Global environmental governance guides national governance efforts in planning and operationalizing mitigation policy. However, the degree to which different environmental issues have been institutionalized within the broader scope of global environmental governance differs widely. Climate change has emerged as a priority issue over the past decades, and its governance has become formalized through the introduction of a number of formal treaties that set out obligations for different parties (Coen et al. 2020). In contrast, no coherent global water governance system exists, although there is a small number of formal treaties that cover important aspects of water governance, such as the Water Convention. As a result, water governance at the global level is fragmented, and water as a supra-regional or global issue is typically not given the prominence it needs.

This chapter demonstrates that to date, as the connection between water and climate mitigation is not well understood, the two are often treated as separate issues, and governed by different frameworks and instruments. This set-up, where issues are conceptualized and governed separately, creates siloed approaches. As a result, the identification of risks and utilization of synergies across the different issues are not capitalized on to the extent needed. This is a missed opportunity. As this report illustrates, the success of climate mitigation efforts is linked intrinsically with water (Part II); achieving climate mitigation thus requires the climate and water communities to acknowledge these interconnections and address them through integrated approaches that mainstream water considerations into climate change mitigation policies, investments, and practices (Part III).

To make this case, this chapter reviews global and national frameworks and instruments that exist for different environmental issues, including climate and water. It then explores the synergistic nature of different environmental issues, as well as the critical importance of cross-sectoral collaboration.

3.2 Overview of global environmental governance frameworks and national instruments

This section examines specific 'governance products': the international and national frameworks and instruments that have been developed to steer and address climate, water, and other environmental issues (see Figure 3.1).

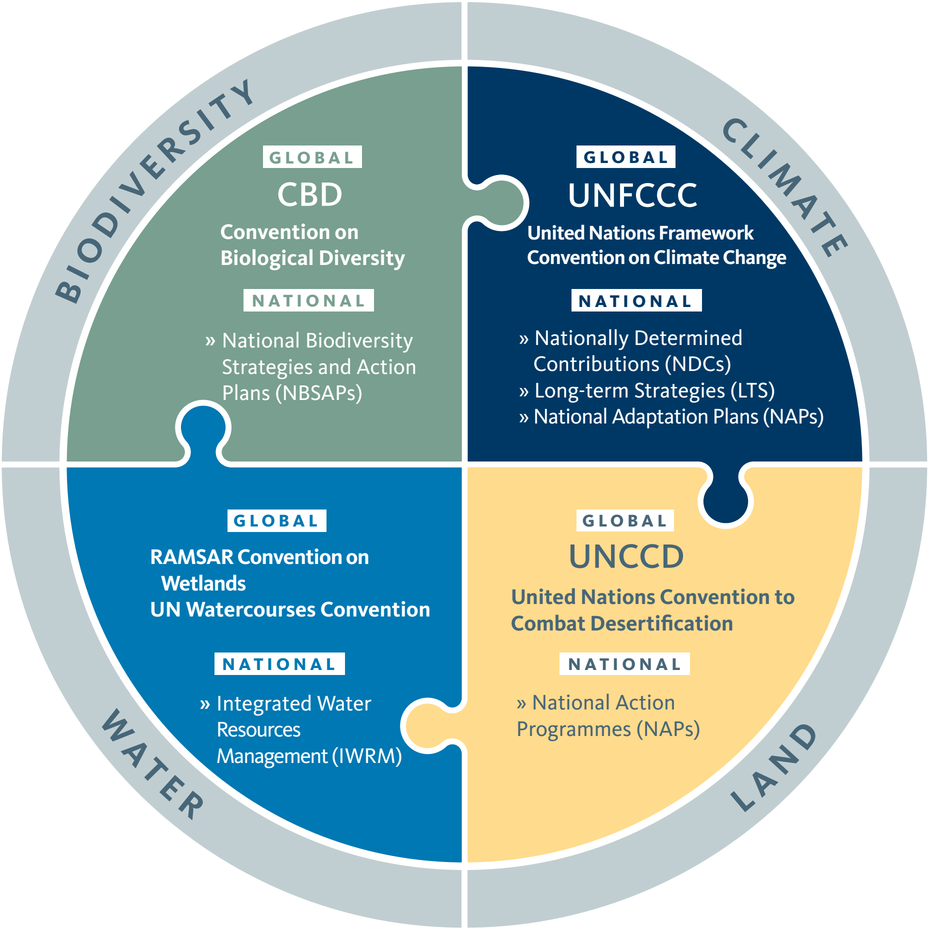

Figure 3.1. Global environmental governance frameworks and national instruments. Source: SIWI.

At the international level, Multilateral Environmental Agreements (MEAs) are becoming increasingly important components of environmental and sustainable development governance as human impacts on the planet intensify. MEAs are formal mechanisms to resolve environmental problems that transcend national boundaries by harmonizing approaches, sharing knowledge and tools, and enhancing access to financial resources (Steiner et al. 2003). Of particular importance are the three conventions emanating from Agenda 21 and established at the United Nations Conference on Environment and Development in 1992 in Rio de Janeiro, thereafter called the Rio Conventions (UN 1992). These include the UNFCCC, CBD, and UNCCD. At the national level, MEAs include instruments setting out how national governments ought to fulfil commitments set out by the MEAs. For example, under the UNFCCC, the Paris Agreement requests each country to outline NDCs, the CBD requests each country to set out NBSAPs, and the UNCCD binds countries to National Action Programmes.[1] As participation of non-state actors in governance is increasing (section 3.3), new types of steering mechanisms beyond the traditional legal binding agreements negotiated by states are also emerging (Biermann and Pattberg 2012). Public-private and private-private norm-implementing mechanisms therefore increasingly complement traditional intergovernmental regimes.

In addition to the three Rio Conventions, three global frameworks, all agreed in 2015, are important: the Paris Agreement, the 2030 Agenda for Sustainable Development, and the Sendai Framework for Disaster Risk Reduction (Sendai Framework). To implement these, states set national implementation plans with national targets. The Paris Agreement is discussed further in section 3.1.1. The 2030 Agenda, discussed further in section 3.1.4, serves as an overarching agenda for global development, and includes goals of economic, social, and environmental nature. It thus takes a holistic perspective on sustainable development and makes a strong case that most aspects of society, development, sustainable growth, and the environment are symbiotic and can only be achieved together (UN-Water and UNESCO 2020). The Sendai Framework is a non-binding framework, designed to achieve: “the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries” (UNDRR 2015). Similar to Agenda 2030, this framework is particularly critical when it comes to showcasing the importance of taking a holistic approach. The key objective of the framework is to increase resilience and reduce long-term risk from both sudden and slow-onset hazards, of which climate mitigation and adaptation are key components (Briceño 2015). Moreover, although water is not featured prominently in the framework, it is of vital importance to fulfil the targets as water-related events such as floods and storms account for a significant proportion of all natural disasters. Research shows that floods accounted for 44 per cent of all disaster events recorded between 2000 and 2019. Extreme events have also become more prevalent, with flood-related disasters recorded since 2000 seeing an increase of 134 per cent compared with the two previous decades (WMO 2021).

The main treaty-based international and national frameworks and instruments for climate, land, development, and water are reviewed in further detail below. Reviewing existing frameworks and instruments makes it clear that the conceptual separation of climate, land, development, and water leads to a fragmented system and creates barriers for integrated approaches (section 3.3). Moreover, the fragmented nature of global water governance means that it is challenging to align water with mitigation efforts in a coherent manner. This is a missed opportunity for climate mitigation that we cannot afford.

3.2.1 Governance frameworks for climate change mitigation

The origins of the current climate change governance system can be traced back to the first World Climate Conference organized by the World Meteorological Organization (WMO) in 1979. While the first global conference on the environment was held in Stockholm in 1972, it was not until 1979 that the scientific community came together and jointly expressed the view that climate change poses a serious threat to humanity. In 1988, WMO and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC), and in 1990 IPCC published its

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[1] NDCs, NBSAPs and National Action Programmes are all discussed in more detail in subsequent sections.

first assessment report.[2] Also in 1990, the United Nations General Assembly launched the Intergovernmental Negotiating Committee (INC) to negotiate a framework convention on climate change. At the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, INC6 adopted the UNFCCC (UNFCCC 1992). In 1994, UNFCCC entered into force with the start of the meetings of the Conference of the Parties (COPs), COP1 being held in 1995 in Berlin. While adaptation was included from the outset (Article 4), UNFCCC focused initially on mitigation, i.e., the reduction of greenhouse gas (GHG) emissions by industrialized countries. This initial emphasis on mitigation has continued to permeate many of the different instruments that materialized later, as discussed below.

The history of global climate change governance frameworks: From Kyoto to Paris

The trajectory of the global effort on emission reduction has been defined by the following major landmarks: the adoption of the legally binding Kyoto Protocol in 1997, the negotiation impasse in Copenhagen in 2009, and the Paris Agreement based on voluntary contribution commitments adopted in 2015. The approach to climate change under the Kyoto Protocol – with a primary focus on mitigation – was focused on legally binding emission reduction[3] by industrialized countries. In 2009, expectations were high prior to COP15 in Copenhagen to deliver a new framework in the post-Kyoto world. However, expectations were far from met, with the sitting United Nations climate chief Yvo de Boer questioning whether this perceived global diplomatic debacle would "spell the end of the UNFCCC process" (de Boer quoted in Vidal 2010). A negotiation impasse was experienced in Copenhagen in 2009 due to new emission trends across countries, including emerging markets.[4] However, in hindsight, COP15 was a significant turning point, prompting the shift towards a more polycentric global climate change regime (Bäckstrand and Lövbrand 2019). What can be seen in its aftermath is not one regime but many: a 'regime complex' consisting of overlapping, complementary, and sometimes even conflicting regimes with multiple centres of authority (Keohane and Victor 2016; Widerberg et al. 2016). Subsequent negotiations thus departed from the top-down, legally binding emissions target approach, moving to inviting pledges of voluntary commitments to cut emissions based on contributions defined by each nation individually, which came to be known as NDCs in the following years (Kuyper et al. 2018) Post-COP15, there was also a shift to transparency rather than legal enforcement, and recognition of the need to mobilize finance from public as well as private sources (Coen et al. 2020). The Copenhagen Accords thus contained and set the stage for much of what was to be incorporated in the Paris Agreement.

The Paris Agreement on Climate Change, a legally-binding landmark accord adopted by nearly all sovereign parties (196) at COP21 in 2015, provides a global framework for addressing climate change by: "holding the increase in global average temperature to well below 2°C above pre-industrial levels" and "pursuing efforts to limit it to 1.5°C" (UNFCCC 2015). To achieve this long-term goal, countries need to undergo economic and social transformation to ensure emissions peak as soon as possible and reach net zero emissions in the second half of the century using NDCs as the main vehicle. Relying on five-year cycles of stocktakes of NDCs and increasing commitments/ambitions, the success of the Paris Agreement hinges on the ratcheting of ambitious targets along the way (UNFCCC 2021b, 2021d). The mid-century low-emission development strategies known as LTS, which set the goal of net zero emissions in the second half of the century, are to set the pace for emission reduction. While the Paris Agreement is legally binding once it is ratified by a country, there is no enforcement mechanism. Instead, the intention is to foster compliance through transparency via publicly available NDCs.

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2. IPCC prepares comprehensive assessment reports about the state of scientific, technical, and socio-economic knowledge on climate change. These reports represent the 'gold standard' scientific resource on climate change. The reports also outline impacts and future risks, and options for reducing the rate at which climate change is taking place. New assessment reports based on the latest scientific knowledge are released every six or seven years.
3. Quantified Emission Limitation or Reduction Objectives (QELROs)
4. In 2007, China overtook the United States as the highest gross emitter of GHGs. This prompted a shift in focus from historical emissions to emission trajectories of emerging markets, in particular China, but also Brazil, India, Mexico, and South Africa.

National climate change governance instruments: NDCs, LTS and emissions mitigation reporting

At the national level, the Paris Agreement is implemented through countries' voluntary commitments that are nationally determined: the NDCs. NDCs outline countries' efforts to reduce GHG emissions and adapt to climate change.[5] These commitments become legally binding once the NDC has been ratified by the country's legislative body. By providing a comprehensive framework for a country's climate action, NDCs usually build on existing climate action, and on sectoral and development plans and policies. Countries are advised to establish a complementary institutional mechanism comprising various key line ministries, including finance and development, to devise an integrated approach to the country's NDC process. Following guidance by the UNFCCC and other institutions, the selection of priority sectors is likewise often based on pre-existing mitigation[6] or adaptation[7] plans, as well as additional scenario analyses completed for the NDC process. The resulting emission reduction targets are formulated as 'unconditional', meaning a country commits to the implementation through domestic resources, or as 'conditional', where the commitment depends on the availability of international development finance. NDCs also outline the policy ecosystem, ongoing projects, country context, planning and implementation process, financing, and monitoring and reporting processes.

The first round of NDCs saw water included in mitigation as part of emissions reduction through renewable energy in the energy sector (hydropower, hydrogen, solar water heaters in buildings), as well as in agriculture (solar water pumping and distribution), land use (wetlands, peatlands), and the waste sector (wastewater treatment and reuse) (see Box 3.1).

Box 3.1. Uganda's first NDC: Building resilient communities, wetland ecosystems, and associated catchments

Wetlands play a particularly important role in Uganda where they serve as natural water reservoirs and help to sustain traditional rain-fed agricultural productivity. In the dry season, the 4 million people living in these areas can still access water to grow crops to feed their families or use the wetland fringes as pasture for animals. The wetlands also act as breeding grounds for large-scale fisheries.

Uganda's wetlands are increasingly seen as an important defence against the onset of climate change. They regulate flooding and remove pollutants from storm surface runoff before the water enters lakes and other water bodies. In addition, they play a critical role in continuously recharging groundwater sources. Uganda has lost around 30 per cent of its wetlands in the last 15 years due to degradation and encroachment, which in turn has exacerbated a series of ecological problems. These include increased flooding as the wetlands lose their water catchment capacity, reduced productivity of farmers living around the wetland fringes, and the silting up of water bodies. This ultimately poses a threat to national water supplies. The conservation of healthy wetlands also has the potential to counter rising GHG emissions. While there are no precise figures for the carbon sequestration of Uganda's wetlands, studies have shown that they can store and release GHGs.

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[5] The Paris Agreement is also the first place where adaptation efforts were integrated to equal the status of mitigation. While a balanced allocation between mitigation and adaptation had already been included in the 2009 Copenhagen Accord, referring to what later became the GCF, the Paris Agreement formalized this approach further. The increasing attention and support for adaptation, and growing emphasis on adaptation by the G-77, culminated in the Paris Agreement, Article 2, which elevated adaptation to be on par with mitigation. A call for action on adaptation emerged in 2001 due to new climate impact evidence from the second and (especially) third IPCC reports, which culminated in the landmark Marrakech Accord, adopted by COP7 in 2001, recognizing for the first time the intrinsic relationship between development and climate change issues (Helgeson and Ellis 2015). With further evidence of climate vulnerabilities, the Bali Action Plan at COP13 in 2007 established adaptation as one of the four pillars under the UNFCCC. At COP16 in 2010, Parties highlighted adaptation with the same level of priority as mitigation and adopted the Cancun Adaptation Framework and established NAPs for least-developed countries (LDCs) to develop medium- and long-term adaptation planning. COP has since invited non-LDCs to undertake NAPs, and many have launched 'NAP equivalent' processes that follow the spirit of the UNFCCC NAP guidance, if not all of its specific steps. It is likely that COP26 in Glasgow and COP27 in Egypt may also advance the establishment of a Global Goal on Adaptation (via the Glasgow Sharm el Sheik Work Programme).

[6] Pre-identified mitigation actions based on Nationally Appropriate Mitigation Actions, UNFCCC reporting through National Communications, low emission development strategies, Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) strategies, CDM projects and others.

[7] Based on NAPs, National Adaptation Programmes of Action, National Communications, National Planning documents, and disaster risk reduction plans.

Box 3.1. Cont.

Uganda was among the few countries to incorporate wetlands into their first NDCs, and one of the very few that did so for both mitigation and adaptation actions.

Uganda's first NDC regarding wetlands:

	NDC climate measures
Mitigation	Development of enabling environment for wetland management, including: • Creation of national information database through re-inventory and assessment of all wetlands. • Design and implementation of 11 RAMSAR site wetland research, eco-tourism and education centres. • Design and implementation of 111 District wetland action plans, with carbon sink potential. • Design and implementation of 15 RAMSAR sites and framework wetland management plans. • Demarcation and gazettement of 20 critical and vital wetland systems and their maintenance countrywide as carbon sinks. • Wetlands law enforcement and governance. • Strengthening wetland management institutions responsible for wetlands management and conservation. • Overall, increase wetland coverage to 12% by 2030, from approximately 10.9% in 2014, through demarcation, gazettement, and restoration of degraded wetlands.
Adaptation	Water sector: • Managing water resource systems, including wetlands, particularly in cities, in such a way that floods are prevented, and existing resources conserved (through the establishment of an IWRM system).

One project example contributing to Uganda's NDC is the Building Resilient Communities, Wetland Ecosystems and Associated Catchments in Uganda project. Financed by GCF and supported by the United Nations Development Programme, Uganda is currently implementing a wetlands project which restores an estimated 760 square kilometres of degraded wetlands and associated catchments, while improving the lives of at least 500,000 people directly, and more than 4 million indirectly, across 20 districts in the eastern and south-western areas of Uganda. The regions have experienced the highest levels of wetland degradation and climate change impacts. The project is employing a three-pronged approach, including restoration of wetlands and associated catchments, improved agricultural practices and alternative livelihood options in the wetland catchment areas, and strengthening farmers' access to climate and early warning information. While focused on climate change, this project is also introducing measures to support gender empowerment, specifically preventing gender-based violence motivated by the impact of droughts.

Overall, based on the first NDC, the Government of Uganda has bigger plans: it aims to increase the current 8 per cent coverage of wetlands across the country to 12 per cent. With nearly 70 per cent of Uganda's population relying on agriculture, measures to enhance people's resilience to climate change are vital. For its revised NDC, Uganda has indicated that it is adding an assessment of the mitigation potential of wetland conservation. However, in the interim submission presented in October 2021, this was not yet included.

Source: UNDP-SIWI Water Governance Facility (2023).

Based on an initial review of new or enhanced NDCs in the most recent round by UNFCCC, 21 per cent of the countries chose to include wetlands and 22 per cent included wastewater in their mitigation strategies (UNFCCC 2021e). The new or revised NDCs also show another uptick in renewable power, including hydropower and the production of hydrogen (UNFCCC 2021c) (Box 3.2).

Box 3.2. Water and mitigation in the latest NDCs

In the last two years (2020–2021), countries around the world have been preparing updates to their first NDC or preparing their second, enhanced NDC as part of international climate change processes. The purpose of an NDC is to outline a party's commitments or contributions regarding climate change under the Paris Agreement, mainly in terms of mitigating GHG emissions but also adaptation measures as part of Adaptation Communications if desired by the party. Notably, many parties chose to include substantive adaptation policies, measures, and targets within their enhanced NDCs.

As of 4 January 2022, a total of 157 new or enhanced NDCs had been received by the UNFCCC, including 114 from non-Annex 1 parties and 43 from Annex 1 parties.[8] NDCs from Annex 1 countries focus on mitigation commitments, whereas most non-Annex 1 countries contain a mixture of mitigation and adaptation commitments.

In terms of mitigation, most parties included modelling and estimates of mitigation activities in the broad categories of Energy, Agriculture, Forestry and Other Land Use (AFOLU), Industrial Process and Products Use, and Waste. All these categories either include water-related components or are reliant on water sources to be effective, but few enhanced NDCs from non-Annex 1 countries outlined specific water-related mitigation measures or recognized specific dependencies or impacts on water resources.

As a general observation, water-related activities featured far more prominently within enhanced NDCs compared with the first iterations (made between 2015 and 2019). Water-related policies and measures continue to be found far more frequently within adaptation sections of these NDCs. Nevertheless, measures around wastewater, climate smart agriculture, waste management, and wetlands are examples of water-related activities found within mitigation sections, and these received increased prominence compared with the first round.

REF: SIWI/GIZ NDC study (forthcoming).

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[8] Annex I Parties include the industrialized countries that were members of the Organisation for Economic Co-operation and Development in 1992, plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States. Non-Annex I Parties are mostly developing countries. Certain groups of developing countries are recognized by the Convention as being especially vulnerable to the adverse impacts of climate change, including countries with low-lying coastal areas and those prone to desertification and drought. Others (such as countries that rely heavily on income from fossil fuel production and commerce) feel more vulnerable to the potential economic impacts of climate change response measures. The Convention emphasizes activities that promise to answer the special needs and concerns of these vulnerable countries, such as investment, insurance, and technology transfer.

Recognizing that many adaptation actions also result in emission reductions (Article 4, paragraph 7), the Conference of the Parties, the supreme body of the UNFCCC Convention's (CMA)[9] Annex to the Paris Agreement guides parties to provide information on mitigation co-benefits from adaptation and economic diversification (UNFCCC 2021a).[10] For example, restoring wetlands not only helps wetland ecosystems adapt to climate change, but also keeps wetlands from becoming major emission sources themselves. Indeed, guidance on NDC design, enhancement, and implementation acknowledges the potential for synergies (but less for conflicts) for mitigation and adaptation goals (GWP 2019; Huq et al. 2018; Smith et al. 2019). Building on the CMA guidance for mitigation co-benefits, the guide on NDC enhancement states that "if adaptation actions are expected to lead to GHG emissions reductions, it is important to take such effects into account in the mitigation planning and target setting to avoid underestimation of the mitigation potential and to make that fact explicit to avoid 'accidental double-counting'" (WRI and UNDP 2019a: 530; Box 3.3).

However, on a practical level, few countries chose to quantify and include such mitigation co-benefits in their emission targets. Assessing the specific mitigation potential of adaptation actions and including them in mitigation targets can constitute a commitment. Making such commitments depends on the country's priorities and financial situation. For example, for a highly vulnerable sector such as agriculture which is intimately linked to food security, livelihoods, and national economy, adaptation will have to be prioritized, and the country will be less able to commit to a specific emission reduction target, even when such benefits accrue. In this situation, countries may prefer to propose vulnerable sectors under the adaptation component only and refer to potential mitigation benefits without quantifying them. When countries can commit to a mitigation target or action, the target can be offered as an unconditional or conditional target, with the latter being subject to international financial support (which still gives countries room to focus on the adaptation goal).

In support of the global climate neutrality goal for the second half of the 21st century, the Paris Agreement (Article 4, paragraph 19) invites countries to submit long-term low GHG emission development strategies, now commonly referred to as LTS. These plans provide a visionary roadmap for achieving net zero emissions by mid-century through economic and social transformations, with a perspective of at least 30 years. While this call was addressed particularly to developed countries, all countries benefit from developing a long-term plan to avoid maladaptation, as well as 'mal-mitigation', which includes water-related risks resulting from poor mitigation planning. In addition, proposed climate actions and economic diversification are best viewed from a long-term climate and development perspective to avoid costly, carbon-intensive lock-ins. For vulnerable developing countries, LTS could be a particularly useful tool to identify climate action pathways that do not put water security at risk when planning adaptation as well as mitigation measures.

Overall, the UNFCCC has experienced various important developments: a) a shift from targeting industrial country emissions in a legally binding manner under the Kyoto Protocol to mandating voluntary contributions from all countries under the Paris Agreement using NDCs; b) moving from the top-down Kyoto architecture to a more bottom-up approach with national plans under Paris; c) broadening out from a primary mitigation focus under Kyoto to a triple goal comprising mitigation, adaptation, and finance under the Paris Agreement; and d) acknowledgement of the need for long-term resilience and net zero ambitions for the second half of the 21st century (Kuyper et al. 2018; UNFCCC 2021b, 2021d).

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9. What is the CMA? "The Conference of the Parties, the supreme body of the Convention, shall serve as the meeting of the Parties to the Paris Agreement. All States that are Parties to the Paris Agreement are represented at the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA), while States that are not Parties participate as observers. The CMA oversees the implementation of the Paris Agreement and takes decisions to promote its effective implementation" (UNFCCC 2021a).

10. CMA 1/10 "Recognizes that each Party with a nationally determined contribution under Article 4 of the Paris Agreement that consists of mitigation co-benefits resulting from its adaptation action and/or economic diversification plans consistent with Article 4, paragraph 7, of the Paris Agreement shall provide the information referred to in Annex I as applicable to its nationally determined contribution and as it relates to such mitigation co-benefits." "Recognizes that each Party with a nationally determined contribution under Article 4 of the Paris Agreement that consists of mitigation co-benefits resulting from its adaptation action and/or economic diversification plans consistent with Article 4, paragraph 7, of the Paris Agreement shall follow the guidance contained in Annex II as it relates to such mitigation co-benefits. CMA 1/16 Annex I: "Mitigation co-benefits resulting from Parties' adaptation actions and/or economic diversification plans, including description of specific projects, measures and initiatives of Parties' adaptation actions and/or economic diversification plans."

Box 3.3. The treatment of water-related GHG emissions in the IPCC guidelines for emission reporting

The NDCs complement the preceding reporting tools for climate change such as National Communications and associated Biannual Update Reports, documents submitted periodically to UNFCCC.[11] The National Communications reporting is informed by a set of guidelines developed by IPCC, an inter-governmental body of the United Nations mandated to provide objective scientific information on climate change. The guidelines focus on the highest emitting sectors: energy; industrial processes; solvent and other product use; agriculture, land-use change and forestry; waste; and others. The water sector is not one of them.

The 1996 Revised IPCC Guidelines (IPCC 1996) included the following water-related components:

- Wetlands and rice cultivation – irrigated versus rainfed (under Agriculture, land use and land-use change).
- Water heating and cooling, as well as emissions from water pumping and distribution may have been included indirectly through energy in residential and commercial buildings, and industrial activities.
- Wastewater – both industrial and residential (under Waste).

Under the Paris Agreement, countries are making the transition from National Communications to the **Enhanced Transparency Framework (ETF)**, which encourages them to submit biennial transparency reports (BTRs) and national inventory reports by 2024 (Annex 1 countries by 2022). Originating from the Katowice climate package (COP24), ETF adopted a detailed set of modalities, procedures, and guidelines (MPGs). The final biennial reports for developed countries are due no later than 31 December 2022 (decision 6/CP.25). Parties under the Paris Agreement are required to submit their first report (BTR1) and national inventory report, if submitted as a stand-alone report, in accordance with the MPGs, at the latest by 31 December 2024 (UNFCCC 2022).

Wastewater, according to the IPCC Guidelines, can be a source of methane when treated or disposed of anaerobically or when dissolved methane enters aerated treatment systems. It can also be a source of nitrous oxide emissions. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006) improved calculations for wastewater in various aspects, including clarifications and new additions. For instance, the methane emission factors for wastewater discharged to aquatic environments were updated and a new emission factor for discharge to reservoirs, lakes, and estuaries was introduced. The calculation of methane emissions from effluent discharged to aquatic systems has been updated to include the discharge of treated effluent and to reflect the removal of organics that occurs during treatment. As for carbon dioxide (CO_2) emissions, only non-biogenic (fossil) CO_2 emissions from wastewater treatment and discharge are considered, but not biogenic, organic matter stemming from human excreta or food waste.

Another important addition to the IPCC Guidelines was the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC 2014). Wetlands play a critical role in the global carbon cycle, storing significant amounts of CO_2 and methane. Wetlands are also the largest natural source of methane (30 per cent) and could release substantially more under future warming scenarios. At the same time, their potential to sequester carbon has largely remained untapped (Anisha et al. 2020; Zhang et al. 2017). The Wetlands Supplement provides updated data, clarifications, and filling of information gaps. It covers inland organic soils and wetlands on mineral soils, coastal wetlands including mangrove forests, tidal marshes, and seagrass meadows, as well as constructed wetlands for wastewater treatment (IPCC 2014).[12]

Thereafter, the 2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories made further clarifications, e.g., regarding flooded lands. Overall, the 2019 revision of the IPCC Guidelines saw a tweaking of

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[11] National Communications describe the national circumstances, national GHG emissions profile, and possible mitigation and adaptation options, and identify needs. The NDC takes the National Communication, which outlines what can be done, a step further, by laying out what a country commits to do.

[12] The 2006 IPCC Guidelines on wetlands covered only peatlands drained and managed for peat extraction and conversion to flooded lands and offered limited guidance for drained organic soils.

Box 3.3. Cont.

the main categories and refinements in the sub-components of reporting with minor adjustments of relevance for water management. This resulted in wetlands being included under Agriculture, forestry and other land use (IPCC 2006, 2019a, 2019b).[13,14]

Whereas the guidelines acknowledge that nitrous oxide emissions can stem from wastewater treatment plants or from "receiving aquatic environments following the disposal of untreated or treated wastewater effluent", its guidance focuses on the former: "how to estimate the nitrous oxide produced during wastewater treatment and sludge treatment that *occurs within the wastewater treatment system, and disposal of the wastewater* (IPCC 2019a; 2019d). The reason for the inclusion of the wastewater treatment system, according to the IPCC, is that "more recent research and field surveys had revealed that emissions in sewer networks and from nitrification or nitrification-denitrification processes at WWTPs [wastewater treatment plants], previously judged to be a minor source, may in fact result in more substantial emissions" (IPCC 2019a; 2019d). Therefore, wastewater treatment and discharge for domestic and industrial sectors[15,16] should be reported, as are emissions from untreated wastewater if discharged into a pooled entity. It is noteworthy, however, to point out that the **emissions released from water bodies polluted by untreated wastewater are likely to be underestimated and under-reported** (see Chapters 4 and 5).

Aside from the refinements relating to Nature-based Solutions (NbS) and wastewater treatment, current IPCC guidelines do not take into account the risk and synergy dimensions that water provides (HLPW 2018; WWC 2017), possibly affecting environmental integrity. Guidance on the design of Intended Nationally Determined Contributions (INDCs), Enhanced NDCs and NDC implementation draws attention to potential sectoral synergies (but does not caution the risk of adverse interactions) (Ricardo-AEP and CDKN 2015; UNDP et al. 2020; WRI and UNDP 2015; 2019a; 2019b). The set of sectoral checklists with water interactions to consider for NDC enhancement was developed to help identify water-related issues to consider and address further within climate plans and policies, taking a deeper look at the potential risks and opportunities for water in the NDC process (WGF 2020).

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[13] Subcategories: Wetlands converted to forest land, Wetlands converted to cropland, Wetlands converted to grassland, Wetlands converted to settlements, Wetlands converted to other land, Wetlands remaining wetlands, Peatlands remaining peatlands, Flooded land remaining flooded land, Land converted to wetlands, Land converted for peat extraction, Land converted to flooded land, Land converted to other wetlands.

[14] Flooded lands are defined in the 2006 IPCC Guidelines for National GHG Inventories (Wetlands) as water bodies where human activities have caused changes in the amount of surface area covered by water, typically through water-level regulation.

[15] Methane and nitrous oxide.

[16] The 2019 Refinement includes new guidance on how to estimate nitrous oxide emissions from domestic and industrial wastewater and presents updated guidance to estimate emissions from centralized wastewater treatment plants. The nitrous oxide emission factors for wastewater discharged to aquatic environments have also been updated and the calculation of emissions from effluent discharged to aquatic systems has been updated to reflect the removal of nitrogen that occurs during treatment.

3.2.2 Governance frameworks for biodiversity and land

Biodiversity and land-related issues have, like climate, received significant attention in global governance. Examining their governance, two MEAs are of particular importance: the Convention on Biological Diversity (CBD), and the Convention to Combat Desertification (UNCCD).

Global biodiversity and land governance frameworks: CBD, UNCCD and the United Nations Decade on Ecosystem Restoration

The CBD has three main objectives: a) the conservation of biological diversity; b) the sustainable use of the components of biological diversity; and c) the fair and equitable sharing of the benefits arising from the utilization of genetic resources.

Examining the UNCCD, its main purpose is to combat desertification and land degradation in countries experiencing serious drought and/or desertification. Further objectives include the improvement of land productivity and the rehabilitation, conservation, and sustainable management of land and water resources. Both CBD national biodiversity strategies and action plans (NBSAPs) and UNCCD National Action Programmes can contribute to mitigation of climate change through sustainable management of water resources in ecosystems and agroecosystems that result in the reduction of emissions.

There are clear synergies between achieving land degradation neutrality (LDN) through implementation of sustainable land management, as recommended by UNCCD (Cowie et al. 2018), and implementation of water mitigation measures on productive land. For example, forest landscape restoration (FLR) has emerged as a way to attract synergies in the implementation of the Rio Conventions and develop solutions to challenging environmental and socio-economic issues. The Global Partnership on Forest and Landscape Restoration defines FLR as "an active process that brings people together to identify, negotiate and implement practices that restore an agreed optimal balance of the ecological, social and economic benefits of forests and trees within a broader pattern of land use" (GPFLR 2013). It is believed that FLR can contribute significantly to achieving the CBD Aichi targets, as well as the upcoming 2030 global biodiversity framework targets of reversing desertification and land degradation, mitigating climate change, and enhancing adaptation. The ambitious goals include reaching LDN (Sustainable Development Goal [SDG] 15.3) by 2030, restoring 150 million hectares of land by 2020 within the framework of the Bonn Challenge, and restoring 350 million hectares by 2030 under the New York Declaration on Forests, which is relevant to several of the targets of SDG 15. Should these goals be reached, such activities could significantly mitigate emissions. However, barriers to implementation remain, such as land tenure rights, capacity constraints, harmful subsidies, and financial barriers (FAO and UNCCD 2015). It is also worth noting that the role of water and a functioning hydrology for landscape restoration has so far received very limited attention in the FLR discourse (Tengberg et al. 2018; 2021).

Beyond the CBD and the UNCCD, it is also critical to promote The United Nations Decade on Ecosystem Restoration (2021-2030) as a collective framework to manage land in the coming decade. Launched in June 2021, it aims to prevent, halt, and reverse ecosystem degradation to mitigate climate change emissions, enhance livelihoods, and maintain biodiversity while contributing to the achievement of global ecosystem goals. As per the strategy, the Decade strives to spark a global movement involving actions from governments, civil society, and the public and private sectors, as well as communities and individuals, making it an inclusive global initiative. It will achieve this by focusing on eight ecosystem types: farmlands; forests; freshwater; grasslands, shrublands and savannahs; mountains; oceans and coasts; peatlands; and urban areas (UNEP and FAO n.d.). Critically, the Decade recognizes the significance of freshwater ecosystems and peatlands as key aquatic ecosystems.

Moreover, the impetus on ecosystem-based restoration approaches allows for the links between forests and water to be taken into account. Notably, UNEP and FAO (2021) notes the importance of water-forest links in the Decade's launch report, and stresses that these are taken into account in restoration efforts. With an estimated USD 1 trillion needed for ecosystem restoration to address global environmental challenges, the Decade aims to mobilize these resources through multiple pathways (UNEP and FAO 2020a). The Finance Task Force of the Decade is chaired by the World Bank, and is focused on directing subsidies towards ecosystem restoration, countering economic interests leading to ecosystem degradation, and incentivizing investments in ecosystem restoration (UNEP and FAO 2020b).

National biodiversity and land governance instruments: NBSAPs and National Action Plans

At national level, the NBSAPs are instruments for implementing the objectives of the CBD (CBD 1992: Article 6). The CBD requires countries to ensure that NBSAPs mainstream biodiversity "into the planning and activities of all those sectors whose activities can have an impact (positive and negative) on biodiversity" (CBD 2012). In 2010 the CBD adopted a strategic plan with 20 targets known as the Aichi biodiversity targets that were included in revised and updated NBSAPs (CBD 2010). The NBSAPs have become instruments for achieving several ecosystem-related targets under SDG 15: Life on land, especially for wetlands (15.1), forests (15.2), and mountains (15.4). However, there has been limited progress in achieving the Aichi targets, which highlights the importance of good governance in achieving conservation targets (Buchanan et al. 2020). The Aichi targets expired in 2020, and a new global biodiversity framework is currently being negotiated to guide actions worldwide through to 2030, to preserve and protect nature and its essential services to people. While not yet finalized, the first draft of the framework gives a good indication of the direction it will take. The draft framework makes a strong case for alignment with the SDGs and emphasizes improving or maintaining the connectivity and integrity of natural systems. With regards to the 2030 action targets in the draft framework, two proposed targets are of particular importance in this context. These are proposed Target 2: Ensure that at least 20 per cent degraded freshwater, marine and terrestrial ecosystems are under restoration, ensuring connectivity among them and focusing on priority ecosystems; and proposed Target 8: Minimize the impact of climate change on biodiversity, contribute to mitigation and adaptation through ecosystem-based approaches, contributing at least 10 gigatons of CO_2 equivalent (GtCO2e) per year to global mitigation efforts, and ensure that all mitigation and adaptation efforts avoid negative impacts on biodiversity. As it stands, Target 2 sets a percentage target for restoration and includes terrestrial and freshwater ecosystems, while Targets 2 and 8 both make reference to whole ecosystems and ecosystem-based approaches, which, in theory, should include forest-water linkages, for example. Other targets refer to conservation through various measures, and emphasize effective, equitable, and sustainable management of resources. Furthermore, the targets include socio-economic aspects that are often overlooked when addressing the impacts of natural resources management.

For the UNCCD, National Action Programmes are the key instruments for implementing the Convention. More recently, the UNCCD adopted LDN targets as the guiding principle for implementing the Convention. LDN was also adopted as target 15.3 of SDG 15. The three LDN and SDG 15.3.1 sub-indicators cover trends in land cover, land productivity, and soil organic carbon stocks for monitoring changes in land-based natural capital and to determine the proportion of land that is degraded over the total land area (UNCCD-AGTE 2013).

3.2.3 Governance frameworks for water

Unlike climate, biodiversity, and land, water has not been governed in the same globally coordinated manner and there is no ‘Rio Convention’ or other overarching global framework for water. This has implications for both policy coordination as well as access to financing, especially in the context of climate change mitigation.

Restoration of the Alviso wetlands at the Don Edwards wildlife refuge, California. Source: Shutterstock.

Global water governance: Ramsar Convention, the United Nations Watercourses Convention, and the International Decade for Action

While no overarching framework exists for water, there are global water frameworks of significance, focusing specifically on blue water (see Chapter 2). The Convention on Wetlands of International Importance, especially for waterfowl habitats, otherwise known as the Ramsar Convention on Wetlands, is one of the earliest examples of an environmental MEA and relates specifically to water. Established in 1971, it provides a framework for conservation and sustainable use of wetlands (Steiner et al. 2003). Challenges in preserving, restoring, and protecting wetlands for increased biodiversity, hydrological functioning, and climate change mitigation are global. Wetlands, such as peatlands, are major carbon sinks and it has been pointed out that management objectives for wetlands could become more closely linked to UNFCCC emission targets and the Paris Agreement (AGWA 2020), also see Box 3.1. However, the Ramsar Convention is not one of the Rio Conventions and there is limited coordination and financing of mitigation actions in wetlands linked to the climate regime (Tengberg et al. 2018).

For transboundary water management, the United Nations Convention on the Law of the Non-navigational Uses of International Watercourses, also known as the United Nations Watercourses Convention, is of special importance. Designed as a framework convention, it entered into force in 2014 after a very long and complex process that lasted over 44 years. Its aim is to ensure utilization, development, conservation, management, and protection of international watercourses, and to promote their optimal and sustainable utilization for present and future generations. The convention embraces the principle of equitable and reasonable utilization and lays down certain factors that should be taken into account, including natural factors, such as hydrology, climate and ecology, as well as the conservation, protection, development, and economy of the water resources of the watercourse (Salman 2015). The convention could thus have a bearing on the design and implementation of climate change mitigation measures that require water, but as a framework convention it leaves the details in the specific watercourse agreements to be worked out by the riparian states.

Another example of a global framework in the water context is the 2018–2028 International Decade for Action on Water for Sustainable Development, declared by the United Nations General Assembly. The Water Action Decade commenced on World Water Day, 22 March 2018, and will end on World Water Day, 22 March 2028. The objective of the Decade is to accelerate efforts to meet water-related challenges, as well as to highlight the role of water in achieving the wider sustainable development agenda, including social, economic, and environmental objectives. Specifically the Decade highlights the need for cooperation and partnerships across all levels and sectors to achieve internationally agreed water-related goals and targets. Progress will be assessed at the 2023 Conference for the Midterm Comprehensive Review of Implementation of the United Nations Decade, taking place at United Nations Headquarters in March 2023, co-hosted by Tajikistan and the Netherlands.

National water governance instruments: IWRM

As these two MEAs demonstrate, water has been negotiated at the global level for a long time. In discussions leading up to the United Nations Conference on Environment and Development in Rio in 1992, water was included, and the need for holistic management of freshwater was recognized. As a principle, it was formally recognized in Chapter 18 in Agenda 21. However, while the Rio Conference saw the governance of climate and land formally institutionalized through UNFCCC, CBD, and UNCCD, global water governance has not been institutionalized in the same manner. In the absence of a global water framework, the Dublin principles, established at the Dublin Conference on Water and Development in January 1992,[17] serve as a guide for global water dialogues, and laid the foundation for the concept of integrated water resources management (IWRM). The Johannesburg Conference on Environment and Sustainable Development in 2002 adopted the Johannesburg Plan of Implementation of international commitments on sustainable development, including elaboration and implementation of national IWRM plans. However, many countries have, for a range of reasons, developed or included national IWRM planning without moving to the stage of implementation. While IWRM plans do not explicitly address climate mitigation or land management, most examples to

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[17] The Dublin Principles state that: (i) water is a vulnerable, finite resource; (ii) water management and development should include stakeholders; (iii) water is an economic good; and (iv) women play a central role in management and conservation of water.

date include components related to conservation of ecosystems and biodiversity, considered important for the hydrological functioning of watersheds and river basins. Strengthening these implicit components also provides an entry point for linking IWRM to climate change mitigation. IWRM as envisioned in Agenda 21 (Chapter 18) is now translated into the 2030 Agenda as target 6.5: By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.

3.2.4 Governance frameworks for sustainable development: The 2030 Agenda

The 2030 Agenda for Sustainable Development - materialized through the 17 Sustainable Development Goals (SDGs) - is an ambitious global framework, setting out a trajectory for global development as a whole. Its ambition is noteworthy, not only due to the breadth of issues covered, but also because of its recognition that the issues are all interlinked, with most aspects of society, development, sustainable growth, and the environment being symbiotic (Figure 3.2). The holistic nature of the SDG framework implies that individual goals cannot be treated in isolation; a large number of potential interactions across the 17 goals and associated 169 targets have to be considered by policy-makers (Costanza et al. 2016). Interconnections between different goals can be both positive (synergies) as well as negative (trade-offs). However, positive correlations among SDGs generally outweigh negative trade-offs, especially for SDGs 1 (No poverty), 3 (Good health and wellbeing), 4 (Quality education), 10 (Reduced inequalities), 12 (Responsible consumption and production), and 13 (Climate Action) (Pradhan et al. 2017).

Prior to the SDGs materializing in 2015, 'mainstreaming' was adopted internationally as a key approach to integrate the environmental issues raised in MEAs into national plans and strategies, as well as in sectoral plans and policies (Nunan et al. 2012). Particularly significant was the Poverty Reduction Strategy Paper (PRSP) initiative launched by the Bretton-Woods Institutions in 1999. The message of PRSP was further reinforced through the establishment of the Millennium Development Goals (MDGs) in 2000. For many years, the MDGs were considered to be the main entry point for mainstreaming MEA objectives at the national level, particularly in low-income countries. However, evidence

Figure 3.2. The SDG 'wedding cake'. Source: Azote Images for Stockholm Resilience Centre, Stockholm University (n.d.)

points to the PRSP alone often not being the most effective force for change. In practice, PRSP objectives could be overruled by upstream processes on key policy issues such as fiscal regimes or foreign investment policy, or downstream decisions on specific investments (Bass et al. 2010). For example, even if a PRSP recommended a particular action to mitigate climate change that requires water, it could be ignored in the face of wider water demands. A more holistic understanding was required.

The holistic and multidimensional approach taken by the SDGs provided a new space to address climate mitigation in a coordinated manner, and utilize the synergies that were often not realized through 'mainstreaming'. Looking specifically at the SDGs relevant to achieving synergies between water management and climate change mitigation, these are primarily SDGs 6 (Clean water and sanitation), 7 (Affordable and clean energy), 13 (Climate action), and 15 (Life on land). A closer look at SDG 15 serves to demonstrate why it is necessary to approach the SDGs with a holistic mindset. Achieving SDG 15 is, according to some studies, associated with a high degree of trade-offs with other SDGs (Pradhan et al. 2017). Nevertheless, the IPCC Report on Climate Change and Land (IPCC 2019c) identified SDGs 2, 3, 7, 11, and 12 as directly relevant to achieving target 15.3 on LDN, while SDGs 1, 6, and 13 are considered to be cross cutting. This shows that synergies across SDGs that are related to mitigation are not only possible, but that target 15.3 on LDN can be closely linked to water-related mitigation measures in terrestrial ecosystems, such as forests, grasslands, and wetlands, as well as agricultural lands. Moreover, this also reconfirms the importance of looking at climate and water as well as other environmental issues in an integrated manner.

3.3 Global financing mechanisms and instruments

To realize the objectives set out in the above discussed frameworks, the question of financing has always been of central importance. As it stands today, the financing system is fragmented, with different funding channels, rules, and procedures creating barriers to accessing funding (Bertilsson and Thörn 2020). Moreover, looking across the board at the global landscape for climate finance, it is noteworthy that water and wastewater management is one of the largest recipient sectors for adaptation finance (37 per cent), but still only receives a very small fraction of mitigation finance. In total, water and wastewater management received USD 17 billion of USD 46 billion of adaptation finance in 2019/20, but only USD 1 billion of USD 571 billion of mitigation finance (CPI 2021).

The Global Environment Facility (GEF) was established in 1992 to be the financial mechanism of the Rio Conventions. GEF was thus set up to fund the incremental costs of addressing global environmental problems related to climate change, biodiversity loss, and land degradation. In addition, it has evolved to fund costs related to international waters and persistent organic pollutants. During the past two funding cycles it has also increasingly supported integrated programmes across two or more environmental issues and sectors to foster synergies and address additional drivers of environmental change (Tengberg and Valencia 2018). The next GEF cycle will seek to promote a green, blue, and resilient recovery, and create pathways to an equitable, nature-positive, and carbon-neutral world (GEF 2021). GEF also administers funds established under UNFCCC, including the Least Developed Countries Trust Fund and the Special Climate Change Trust Fund, and acts as interim secretariat for the Adaptation Fund. However, GEF has been subjected to criticism from donors for lacking capacity to scale up project financing, and from recipient countries for problems with access modalities (Bruun 2017).

In response to the criticism, the Green Climate Fund (GCF) was established by the Parties of the UNFCCC at COP16 in Cancun in 2010 as the new primary climate finance mechanism. GCF funds both climate change mitigation and adaptation, as well as cross-cutting interventions. It is guided by an objective to promote a paradigm shift towards low-emission and climate-resilient development pathways (GCF 2020). As such, it focuses on how to facilitate more fundamental system change, as incremental adjustment (e.g. promoted by GEF), is considered insufficient to manage climate change. GCF is therefore increasingly providing guidance to countries on these complex concepts and processes. This has, however, created tension between top-down governance and country ownership (Bertilsson and Thörn 2020).

In addition to GEF and GCF, the 1997 Kyoto protocol set up the Clean Development Mechanism (CDM). Under the Kyoto Protocol, industrialized countries

Starting 2023, the Affric Highlands rewilding project, Scotland, will return 500,000 acres of land to natural processes. Source: Shutterstock.

committed to individual and legally binding targets for GHG emissions. Article 12 defines a CDM whereby high-income countries (Annex 1 countries) earn certified emission reductions through projects implemented in low-income countries. A CDM project activity might involve, for example, a rural electrification project using solar panels or the installation of more energy-efficient boilers. However, several issues, including high transaction costs, have surrounded CDMs, which has resulted in a weak project pipeline (Cowie et al. 2007; FAO and UNCCD 2015). However, since CDMs are not an instrument under the Paris Agreement, the mechanism is currently phased out, which means that selling credits from CDM projects in the market beyond 2021 is unlikely. Instead, a new central mechanism will take its place under Article 6.4 of the Paris Agreement once its rules and regulations have been adopted. Some projects, such as Land-Use Change and Forestry (LULUCF) can also access funding through Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) (see Chapter 6).

Increasingly, market-based mechanisms and private sector actors are being recognized as having a critical role to play. Market-based mechanisms such as Payment for Ecosystem Services (PES) have long been utilized to safeguard wider ecosystem services, including watershed health (Costanza 2020). More recently, Water Funds have been introduced as a vehicle to mobilize investments for water security through solutions grounded on nature-based infrastructure and sustainable management of watersheds. Companies that are deeply embedded in the natural environment through their supply chains, and that rely on these systems to supply water of suitable quantity and quality to produce their goods and services, also have an important role to play (Rudebeck 2019). Increasingly, companies are adopting water stewardship approaches and striving to invest in projects beyond their own operations to mitigate risk and safeguard access to water resources. Increasingly, efforts are being strengthened to mobilize capital directly from the financial services sector. For example, while overseas development assistance is still considered to have a critical role to play, it is often leveraged strategically to mobilize commercial capital through guarantees or blended finance approaches for example, which incentivize commercial capital to flow into bankable segments of projects. Green bonds, blue bonds, and sustainability bonds are other examples of innovative financing mechanisms that have gained substantial traction. Bonds are fixed-income financial instruments, where the proceeds will be used exclusively to finance or re-finance environmental or social projects. While no single source of financing will be enough, collaboration across sectors is the key to mobilize funding more widely. Moreover, while no vehicle can provide a silver bullet, they all have a role to play.

Critically, there is untapped potential to access international climate finance for water-related mitigation measures. Currently, large sums are being committed at the international level to mitigate and adapt to climate change, but only a small fraction of these funds are being directed to water-related mitigation measures. There is an opportunity to tap into these funding sources and redirect funds for investments in water-related projects if such mitigation measures are integrated into the NDCs and other national and sectoral instruments. Most financing committed today, however, is mobilized at the national level; there is still a substantial need to mobilize additional financing for local projects, particularly in low-income countries.

3.4 Achieving climate mitigation through integrated and cross-sectoral approaches

Reviewing existing frameworks and instruments for climate; biodiversity; and land, water, and sustainable development makes it clear that the conceptual separation between the different issues creates a fragmented governance system. This fragmentation in turn creates barriers to identification and funding of more holistic governance approaches where leverage points are utilized to achieve win-win outcomes across the different issues. Moreover, because of the fragmentation of global water governance, there are also inherent fragmentations in water messaging, expertise, and funding, which means that water as an issue is typically not strongly advocated with 'one voice' in the same way as climate, or biodiversity and land, where efforts can assemble under one joint convention. In effect, coherent water messaging is often not featured in a prominent manner. This is of particular significance within climate discussions. While the role of water is acknowledged strongly for climate adaptation, the role of water for climate mitigation is not yet acknowledged to the extent needed to achieve mitigation targets. As demonstrated in Part II, this is a missed opportunity for climate mitigation because to meet climate mitigation targets, water must be mainstreamed into this process.

To better leverage the synergies that exist between climate mitigation and water, as well as between climate; biodiversity; and land, water, and sustainable development more broadly, it is necessary to understand and articulate the leverage points more clearly. For example, there is potential for strong synergies between the three Rio Conventions in LULUCF that can generate significant carbon benefits above and below ground, while also contributing to conservation and sustainable use of biodiversity, and reduction of land degradation and desertification (Cowie et al. 2007; IPCC 2019c). Sustainable management of water resources for forestry and agriculture at the landscape scale can further enhance these synergies, while also contributing to water and food security for local communities (Tengberg et al. 2021). Parts II and III of this report unpack and assess these leverage points in more detail, and demonstrate the value added to climate mitigation potential by holistic management through integrated approaches.

To facilitate integrated approaches and contribute to delivering climate mitigation, it is also critical to strengthen governance (Azizi et al. 2019; Tengberg et al. 2021). This can be achieved, at least in part, through a shift towards a polycentric governance system. Such a system, where different actors operate across a multitude of different scales and centres of power, is necessary because to perform well under conditions of rapid climate change, governance systems themselves must be integrated (coordinated across levels and sectors to enhance synergies and reduce trade-offs) and adaptive (able to respond to new knowledge gained during policy implementation) (Pahl-Wostl 2015). Polycentricity is thus an essential characteristic of integrated and adaptive governance and management systems (Ostrom 2010). Moreover, it has been argued that polycentric systems combine the distribution of power and authority with effective and efficient coordination, and balance bottom-up and top-down governance (Pahl-Wostl 2015).

Inherent to a polycentric system is a distributed centre of power, where different stakeholders dispersed across space and scales contribute to governance efforts. The inclusion of non-public actors in governance, which is a defining feature of the shift from govern*ment* to govern*ance* as a system of govern*ing*, not only contributes to polycentricity, but also creates innovative opportunities for cross-sectoral collaboration. Civil society actors and epistemic communities like non-governmental organizations (NGOs) and advocacy networks play an increasingly important role in policy-making in terms of agenda-setting, knowledge dissemination, and policy implementation (Haas 1992; 2008; Rasche and Gilbert 2012). Similarly, the private sector, including companies and the financial services sector, now contributes extensively to shape environmental policies and deliver on their objectives (Biermann and Pattberg 2008). While companies have a long tradition of engaging with issues beyond core business activities (Fyke et al. 2016; Schwartz and Carroll 2008), efforts to mobilize the financial services sector and enable it to align financial flows with environmental objectives is a fairly new endeavour.

Explaining the growing inclusion of non-state actors, researchers point towards what is typically characterized as the 'governance gap': a growing aperture between the scale at which issues arise (global) and the space in which issues are managed (the nation-state) (Castells 2008). Faced with this gap, it is argued that the public sector suffers from a 'governance deficit': a decline in state capacity – or at least perceived capacity – to deal with complex environmental issues (Delmas and Young 2009; Falkner 2003;Hajer and Versteeg 2005). Part of this is perceived to be an 'implementation deficit': because of the mismatch between complex global environmental issues and availability of national resources, individual governments typically suffer a deficit of material capacity to address the issue at hand. Moreover, because of the disjunction between the need for globally coordinated approaches in supra-territorial spaces and national territorial self-determination, some also point to a 'participation deficit', where negotiated solutions are perceived to lack the appropriate level of stakeholder participation, and by extension democratic legitimacy (Scholte 2002). These gaps create ample opportunities to mobilize – and legitimize – the support and involvement of actors beyond conventional public departments. For instance, the arguments based on the implementation deficit are often drawn upon to rationalize the inclusion of actors from the business sector (Beisheim 2012; Brühl and Hofferberth 2013), and those pointing towards the participation deficit often turn to NGOs as the type of actor with the potential to close this gap, by 'giving voice' to those who would otherwise not be heard (Bernauer and Gampfer 2013; Dany 2012; Teegen et al. 2004). While collaboration across sectors is not without tensions, it is absolutely critical to address complex environmental challenges, such as climate mitigation.

With new types of actors involved, it naturally follows that new types of governance instruments are required. In addition to traditional treaty-based regimes, a range of other mechanisms have therefore emerged, including voluntary and market-based mechanisms. Critics suggest that the replacement of regulatory approaches with market-based and voluntary mechanisms could lead to outcomes that are not aligned with the public good (Brühl and Hofferberth 2013; Mert 2012). However, while there are instances where such critique is valid, it is vital to recognize that it is imperative that these actors become increasingly involved, and new types of mechanisms are required to incentivize involvement.

Interestingly, as the field of actors involved in national governance efforts becomes increasingly complex, it is also a natural consequence that governance becomes more polycentric. These different actors operate across a multitude of different scales and centres of power, from local NGOs to large multinational corporations or financial institutions spanning the Earth, where even national governance is operationalized across multiple levels.

3.5 Conclusions and future outlook

To deliver on climate mitigation at the scale and speed needed, water must be mainstreamed into the climate governance process. However, as this chapter demonstrates, water and climate mitigation are treated as separate issues, governed by different frameworks and instruments. The fragmented nature of global water governance also means that it is challenging to align water with mitigation efforts in a coherent manner. This is a missed opportunity for climate mitigation we cannot afford. At the broader level, this set-up, where interlinked issues such as climate, water, biodiversity, land, and sustainable development issues are conceptualized, governed, and financed separately, creates siloed approaches. By extension, it creates barriers to achieving climate mitigation as leverage points are not capitalized on, and risks are not accounted for. Integrated approaches are needed to overcome these barriers. To better leverage synergies, it is necessary to understand and articulate the potential win-wins more clearly (see Chapter 8) and strengthen governance structures to facilitate approaches that can capitalize on these synergies (Chapter 9).

The following chapters in Part II provide an overview of the mitigation potential of different sectors as they relate to water, collectively attesting that climate and water are linked inextricably, and that climate mitigation cannot succeed without accounting for water.

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CHAPTER 4

Mitigation measures in drinking water and sanitation services

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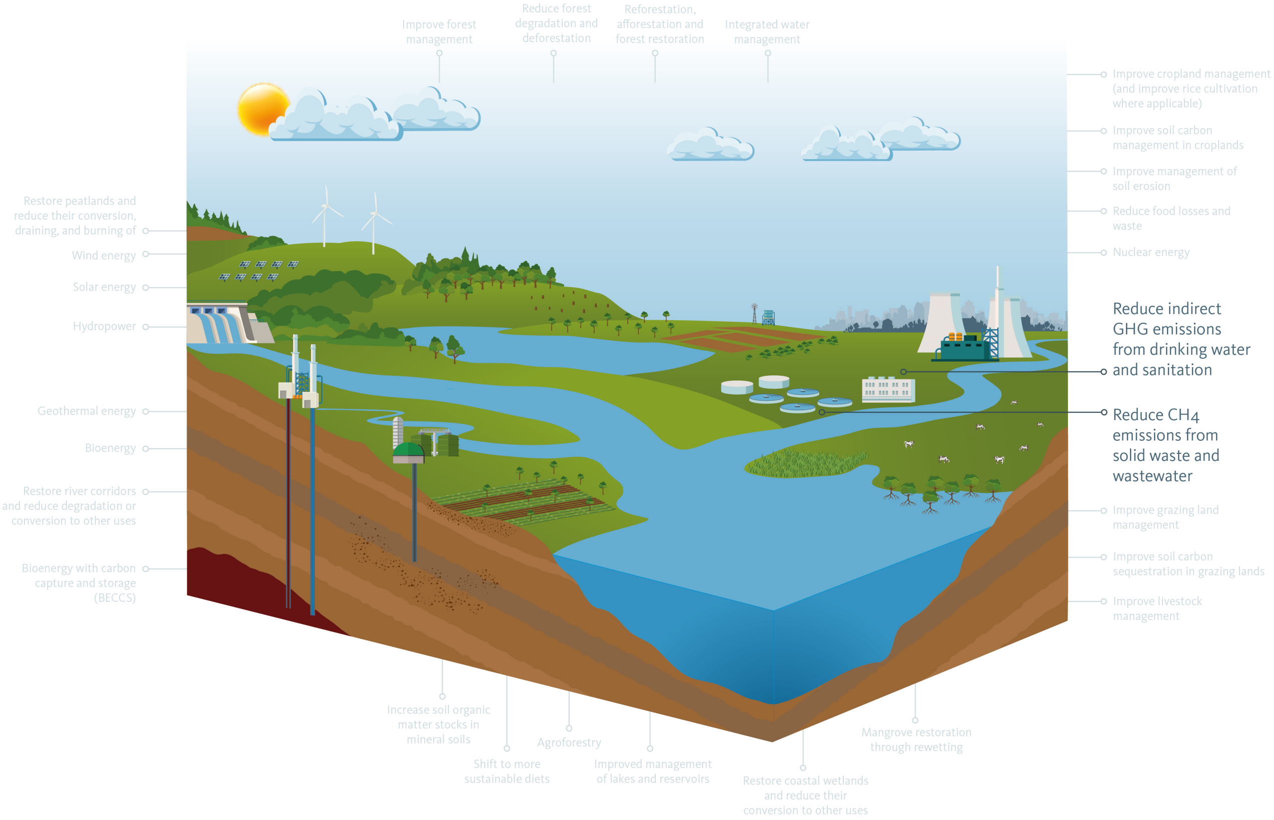

Figure 4.0. Mitigation measures in drinking water and sanitation services. Source: SIWI.

Highlights

- Wastewater treatment and discharge account directly for 12 per cent and 4 per cent of global methane and nitrous oxide emissions, respectively. In addition, drinking water and wastewater management are responsible for approximately 4 per cent of global electricity consumption, often associated with indirect carbon emissions. It is expected that, by 2030, the amount of energy consumed will increase by 50 per cent.
- Reducing the release of these greenhouse gases (GHGs) is a major opportunity for climate change mitigation. Release of GHGs from wastewater and faecal sludge can be reduced through the improved design, management, and adjustment of operating conditions of wastewater treatment plants (WWTPs). Similarly, energy efficiency measures and other solutions (e.g., increased use of renewable energies) can be implemented to decrease energy consumption and reduce carbon dioxide (CO_2) emissions.
- A significant proportion of the wastewater generated in cities and rural areas remains untreated or only partially treated, with the emissions from untreated wastewater being three times higher than emissions from conventional WWTPs. In addition, millions of people currently have limited or no access to sanitation, and the mitigation potential of providing them with access to safely managed sanitation services cannot be underestimated. The extension of wastewater collection and treatment systems, including decentralized solutions, emerges as a win-win for development and climate mitigation.
- Water utilities are increasingly measuring and reporting their GHG emissions and savings as part of national GHG inventories, using tools such as the publicly available Energy Performance and Carbon Emissions Assessment and Monitoring (ECAM) tool. However, there is a need to strengthen assessment, monitoring, and reporting of GHG emissions from water and wastewater handling, including on-site sanitation. The actual mitigation potential is largely unknown because data on GHG emissions is limited and has high levels of uncertainty.
- This data and knowledge gap hampers effective integration of water, sanitation, and hygiene (WASH) in climate policies and mitigation strategies. It also presents a challenge to making climate finance available.

4.1 Introduction

Improvements in the delivery of drinking water and sanitation services can contribute significantly to climate mitigation solutions. The collection, treatment, and discharge of wastewater and faecal sludge result in the direct emissions of significant amounts of methane and nitrous oxide from the decomposition of organic matter. Similarly, the management of water and wastewater systems involves energy-intensive processes and, depending on the source of energy used, contributes indirectly to emissions of CO_2 and other GHGs (Maktabifard et al. 2020). From another angle, water supply efficiency can reduce global emissions through the reduction and control of unaccounted-for water, for example.

The emissions from water and sanitation systems arise from different stages of the value and service chain. They result from either fugitive emissions from biological treatment facilities (direct emissions), or management activities and the demand for resources to run such systems, such as energy and transportation of sludge; the production of chemicals for water treatment and distribution; or processes associated with abstracting, supplying, and treating drinking water (indirect emissions). The magnitude and characteristics of emissions from a given system are highly dependent on its technological configuration and operational arrangements. Other important factors include the features of the water, wastewater, and sludge, and environmental conditions, such as the average seasonal temperatures of a country.

This chapter describes the mitigation measures for various potential adverse impacts resulting from the management of water and wastewater systems. In the next section, global and regional data on GHG emissions from water and sanitation services are presented and discussed. Section 4.3 covers the mitigation options to reduce the direct release of GHGs from wastewater and faecal sludge treatment and discharge. It also addresses the emissions from decentralized sanitation systems. Section 4.4 presents solutions to mitigate the GHGs emitted indirectly through energy-intensive processes related to water and wastewater management. Sections 4.5 and 4.6 present the gaps in climate policy and financing, and in data and knowledge on GHG emissions from water supply and sanitation. Section 4.7 concludes with a list of key action points suggesting the way forward.

4.2 GHG emissions from drinking water and sanitation

4.2.1 Direct GHG emissions from wastewater and faecal sludge management

Wastewater treatment and discharge processes are sources of anthropogenic emissions of GHGs such as CO_2, methane, and nitrous oxide.[1] In coherence with the trends observed during the past decades, these emissions are projected to increase steadily in the future (US EPA 2013). Lu et al. (2018) estimated that direct GHG emissions at WWTPs account for approximately 1.6 per cent of global GHG emissions, stating that wastewater treatment is responsible for roughly 5 per cent of the total global non-CO_2 GHG emissions (e.g., methane and nitrous oxide). In another study, Crippa et al. (2019) showed that in 2018 the sanitation and wastewater sector[2] was responsible for 11.84 per cent of global methane emissions and 4.28 per cent of global nitrous oxide emissions (Figures 4.1 and 4.2). In this same year, wastewater treatment and discharge alone accounted for 57.21 per cent of methane and nitrous oxide combined global emissions from the waste sector. Of those, the share of methane and nitrous oxide emissions corresponded to 51.76 per cent and 5.45 per cent, respectively (Crippa et al. 2019). Figure 4.2 also shows that within emissions of nitrous oxide from the waste sector, wastewater accounted for almost 94 per cent of these emissions (Crippa et al. 2019). According to the Intergovernmental Panel on Climate Change (IPCC) Working Group (IPCC 2014), between 1970 and 2010, the domestic/commercial sector was responsible for close to 80 per cent of the methane emissions from the wastewater category.

More detailed inventories in the United States of America (USA) and European Union (EU) indicate regional disparities. In the USA, GHG emissions from wastewater accounted for approximately 2.8 per cent and 6.2 per cent of total methane and nitrous oxide emissions, respectively (US EPA 2018). A similar EU inventory (EEA 2021) showed that methane emissions accounted for approximately 4 per cent of the total emissions, while nitrous oxide emissions were significantly lower, i.e., 3 per cent of the total emissions. Moreover, in both regions, the trends for the two gases have been different over the last 30 years. In the USA, methane emissions remained stable from 1990 to 2005, and in the last 15 years have decreased by almost 20 per cent. This reduction was attributed to decreasing amounts of wastewater being treated in anaerobic systems. Nitrous oxide emissions were gradually increasing from 1990 until 2015 (altogether by 35 per cent) and then stabilized. The increase was explained by an increasing USA population and protein consumption. However, in the EU, methane emissions decreased by over 50 per cent, while nitrous oxide emissions decreased by almost 17 per cent. These reductions were attributed to the implementation of new wastewater treatment technologies (EEA 2021).

Although relatively small compared with GHG emissions that are released directly from WWTPs, the mitigation impact of decentralized sanitation also requires consideration in planning for sanitation and wastewater systems. More specifically, it is estimated that 1.6 billion people use pit latrines on a daily basis (WHO 2021), roughly accounting for 1 to 2 per cent of current methane emissions (Dickin et al. 2020; van Eekert et al. 2019; Reid et al. 2014). Pit latrines are therefore a significant source of methane in sanitation, as already suggested by Kulak et al. (2017), which states

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[1] The IPCC guidelines suggest that only methane and nitrous oxide emissions are accounted for in WWTPs, while CO_2 emissions are not included as being derived from natural biological sources (IPCC 2014).

[2] The sanitation and wastewater sector includes industrial and domestic categories, comprehending different treatment systems such as latrines, septic tanks, lagoons, and aerobic and anaerobic plants, among others (Crippa et al. 2019).

that closing the sanitation gap through pit latrines would be expected to cause large increases in India's annual GHG emissions, equivalent to 7 per cent of current levels. Along this same line, another study suggests that providing basic services such as pit latrines to 1.69 billion people who lack access to sanitation could double the GHG emissions from this source (van Eekert et al. 2019). These estimates are, however, relatively uncertain, since GHG emissions depend on the type of on-site infrastructure (e.g., pit latrine versus septic tank), the individual use of the system (e.g., poor flush latrines versus dry latrines), the quality and efficiency of faecal sludge management, and the existence and type of faecal sludge treatment, including operational issues and the propensity for anaerobic conditions (Saunois et al. 2016; GIZ et al. 2020).

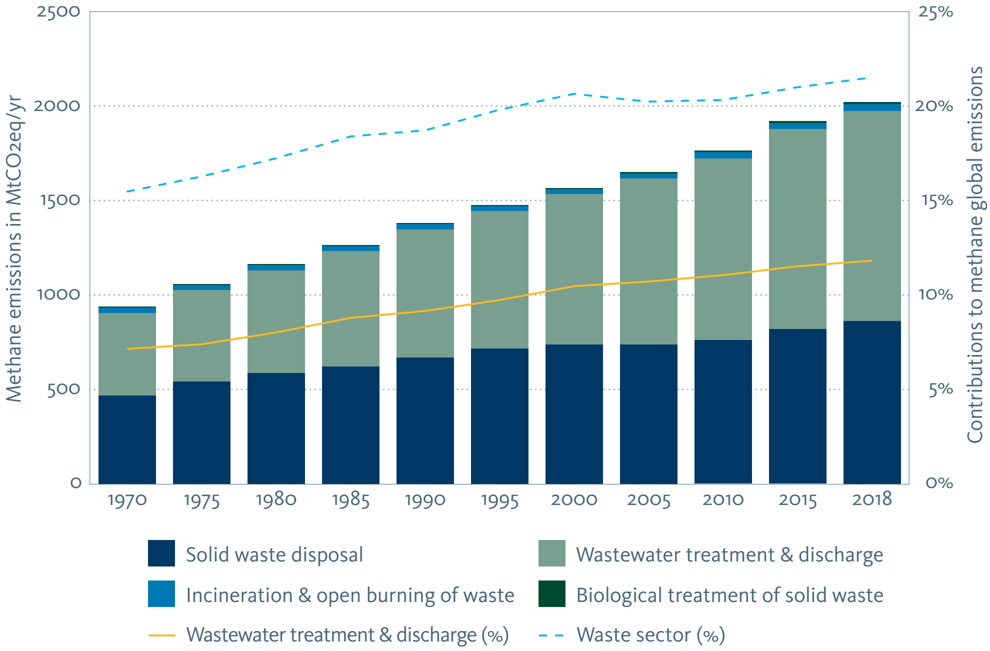

Figure 4.1. Global methane emissions from waste, by activity in the water sector, and percentage contribution to global emissions. Source: adapted from Crippa et al. (2019). Graphs were elaborated based on EDGARv6.0 inventory, which makes use of IPCC 1996 and 2006 codes for specification of the sectors. The 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste was used as a reference for defining the codes included in the waste sector, i.e., Solid waste disposal; Biological treatment of solid waste; Incineration and open burning of waste; and Wastewater treatment and discharge (domestic and industrial).

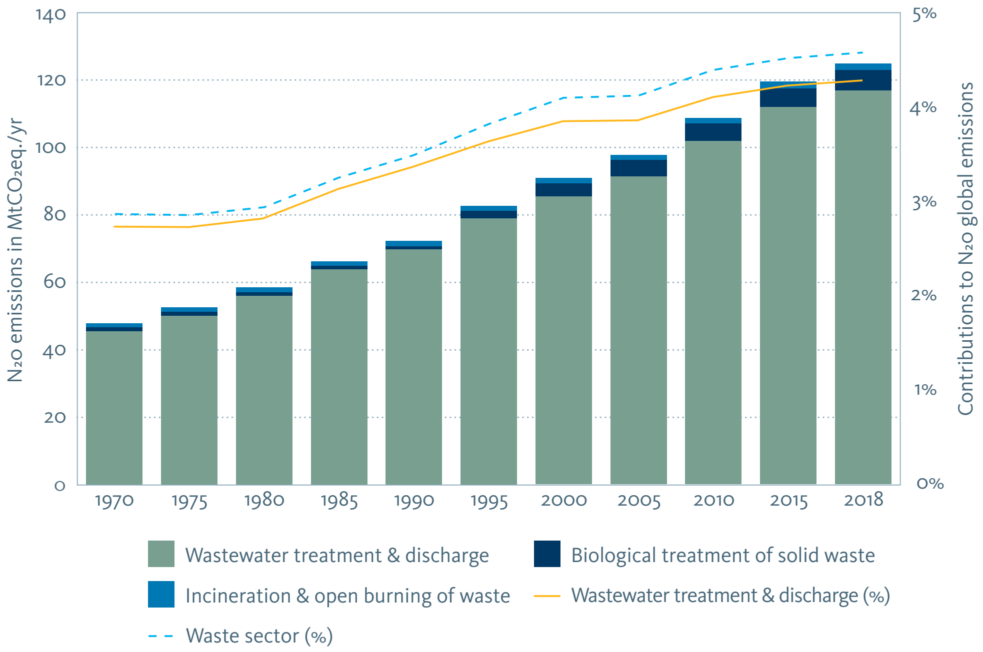

Figure 4.2. Global nitrous oxide emissions from waste, by activity in the water sector, and percentage contribution to global emissions. Source: adapted from Crippa et al. (2019).

4.2.2 Indirect GHG emissions from drinking water and sanitation

The extraction, distribution, and treatment of water and wastewater use vast amounts of energy. It is estimated that the sector[3] globally uses roughly 120 million tons of oil equivalent (Mtoe) per year (IEA 2018), making the proper management of water and wastewater essential to reduce energy usage and associated GHG emissions (Nair et al. 2014). More than half of this energy is in the form of electricity, accounting for 4 per cent of global electricity consumption. About 40 per cent of this electricity is used for water supply, including the extraction of ground and surface water, while wastewater treatment and water distribution account for about 14 and 13 per cent, respectively. About 26 per cent is used for desalination and re-use, and the remainder for long distance water transfers (5 per cent) (IEA 2018). However, as noted by IWA (2022), there is a big difference between high-income and low-income countries. In high-income countries, wastewater treatment makes up about 42 per cent of electricity consumption, whereas in low-income countries, this figure is substantially lower since a large portion of wastewater is neither collected nor treated.

In consequence, for many municipal governments, drinking water supply and wastewater treatment are typically the largest public energy consumers, often accounting for 30 to 50 per cent of total energy consumed (Copeland and Carter 2017; IEA 2018), also representing a significant fraction of municipal energy bills (Capodaglio and Olsson 2019).

By 2030, it is expected that the amount of energy consumed by the water sector will increase by 50 per cent, with upward pressure coming from several sources: a) increased reliance on desalination to bridge the water supply gap in water-scarce regions; b) large-scale water transfer projects; and c) wastewater treatment expansion in developing and emerging economies (IEA 2018).

4.3 Mitigation actions to reduce direct GHG emissions from wastewater and faecal sludge management

In WWTPs, mitigation strategies to measure, reduce, and report direct emissions of GHGs are increasingly common. As shown in Table 4.1, they can focus on both selecting an appropriate process configuration and adjusting operational conditions. However, much of the wastewater generated in cities and rural areas remains untreated or only partially treated, with the emissions from untreated wastewater being three times higher than those of conventional WWTPs (IEA 2018). Therefore, there is an urgent need to expand and improve wastewater collection and treatment, with a special emphasis on low-cost decentralized systems.

Modern urban wastewater treatment plant. Source: Shutterstock.

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[3] Includes water extraction, long-distance water transport, water treatment, desalination, water distribution, wastewater collection, wastewater treatment, and water reuse (IEA, 2018)

Table 4.1. Overview of potential mitigation action to reduce direct GHG emissions (methane, nitrous oxide and CO_2) from drinking water and sanitation

★★★★ High mitigation potential due to efficient reduction of direct GHG emissions and high level of scalability;
★★★ Medium to high mitigation potential due to efficient reduction of direct GHG emissions but not easy to scale-up;
★★ Medium mitigation potential due to less efficient reduction of direct GHG emissions;
★ Low mitigation potential due to low reduction of direct GHG emissions.

MITIGATION ACTION	PROS, CONS, AND CAVEATS	MITIGATION POTENTIAL (MP)
Modify the operational conditions (minimization).	In terms of costs, the most efficient way to reduce GHG emissions is to modify and control the operational conditions of WWTP units (Campos et al. 2016). However, this is not always possible due to the operational limitations of the installed units.	MP: ★★★★ Marinelli et al. (2021) determined direct and indirect emissions from WWTPs in the Treviso region of Italy. The study included five plants of different treatment capacities, ranging from 3,000 to 73,000 population equivalent (PE). The authors prioritized the following systematic GHG mitigation strategies: • Acquire external renewable energy sources to reduce the indirect emissions • Optimize aeration efficiency to reduce dissolved GHGs in the final effluent • Avoid uncontrolled transitory phases in the reactors to reduce direct emissions • Promote low- impact sludge disposal, e.g., farmland distribution. • Use chemical reagents characterized by lower emission factors.
Apply new treatment configurations and processes (prevention).	The configuration of new WWTPs should maximize the anaerobic pathway for organic matter removal and the use of microalgae. Land requirements, however, might hamper the implementation of these solutions in specific contexts (microalgae systems to remove nitrogen would require about ten times the area necessary for activated sludge systems).	MP: ★★★★ One study quantified the potential reduction of GHG emissions due to the implementation of new processes in WWTPs (Campos et al. 2016). Results obtained indicate that systems using microalgae to remove nitrogen are the most suitable systems to decrease GHG emissions during wastewater treatment.
Introduce biogas capture and valorization.	Biogas capture and valorization through a cogeneration system, directly reducing methane emissions and providing renewable energy, which can be used in the WWTP. Emissions and their reductions need to be measured frequently.	MP: ★★★★ In 2014, the water utility in the city of Cusco, Perú (SEDACUSCO), supported by the Ministry of Housing, Construction and Sanitation, and the German Agency for International Cooperation (GIZ), started operating an anaerobic digester for treating sludge and producing biogas on a continuous basis. In this way, SEDACUSCO attained a steady reduction in the amount of untreated sludge it disposed of. In 2021, SEDACUSCO avoided about 8,200 tons of CO_2 equivalent per year, but with the biogas being flared and released into the atmosphere without valorization. In 2021, SEDACUSCO inaugurated a biogas-powered clean energy production system, turning biogas into thermal and electrical energy. It is expected that this new system will help SEDACUSCO to save EUR 260,000 in annual electricity costs and avoid 544 tons of CO_2 equivalent per year in addition to the emissions avoided by the sludge treatment.

MITIGATION ACTION	PROS, CONS, AND CAVEATS	MITIGATION POTENTIAL (MP)
Capture and treat the gaseous streams containing GHGs (treatment).	Various technologies exist to destroy or capture nitrous oxide, methane, and CO_2 from industrial gaseous streams. For instance, traditional technologies, such as selective catalytic reduction and selective noncatalytic reduction, are currently used to control and remove nitrous oxide emissions. Similarly, biological technologies based on biofilter systems have been studied to remove methane from waste gas emissions. However, efficient low-cost mitigation technologies to treat gaseous streams from WWTPs are not yet fully developed. In addition, the capital costs required to cover the different tanks and capture GHG emissions are relatively high (Campos et al. 2016).	MP: ★★ Chou and Cheng (2005) evaluated control methods for volatile organic compounds (VOCs) from WWTPs in Taiwan, and recommended use of a system of sealed covers connected by suction to a purification facility as the optimal technology for controlling VOC emissions in parts per million volume (ppmv) as methane. Cost analysis results indicate that incinerators with regenerative heat recovery are optimal for treating high VOC concentrations exceeding 10,000 ppmv as methane; the resulting cost for abatement VOC emissions is around USD 165 per ton of methane. For a low concentration of 1,000 ppmv as methane, thermal incineration is not recommended as its cost exceeds USD 2,560 per ton methane. Collecting the exhaust from the neutralization and biotreatment stages and then injecting the collected stream into the activated sludge basin via existing blowers is recommended when treating varying VOC concentrations (100–1,000 ppmv as methane). Treatment costs increase from USD 49 to 490 per ton methane as concentration reduces from 1,000 to 100 ppmv. New blowers for injecting exhaust into an activated sludge basin, at a cost of USD 810 per ton methane, are only recommended for concentrations exceeding 1,000 ppmv as methane.
Improve design of decentralized sanitation solutions with specific focus on composting toilets.	Reasons to promote composting toilets have traditionally been unrelated to GHG mitigation. These refer to avoided groundwater pollution and the opportunity for nutrient recycling by reconceiving excreta as a resource. The recognition of the mitigation potential of this solution adds to its existing advantages. However, before scaling up this sanitation solution, better characterization of both methane and nitrous oxide emissions is needed. In addition, the adoption of composting toilets may be limited in some contexts due to socio-cultural barriers relating to reuse and handling of excreta, such as religious practices.	MP: ★★★ Reid et al. (2014) discusses the potential methane mitigation costs of composting toilets, showing that they are competitive with some other measures in the waste management sector like source separation of municipal food waste or upgrading WWTPs to anaerobic treatment with biogas recovery. By computing the marginal abatement costs (MACs), authors show that MACs for composting toilets range from USD 57 to 944 per ton CO_2 equivalent in Africa and USD 46 to 97 per ton CO_2 equivalent in Asia, while averaging USD 134 per ton CO_2 equivalent and USD 193 per ton CO_2 equivalent for solid waste separation and anaerobic wastewater treatment, respectively.
Composting toilet at Airlie Beach, Queensland, Australia. Source: Shutterstock.		

MITIGATION ACTION	PROS, CONS, AND CAVEATS	MITIGATION POTENTIAL (MP)
Promote off-site composting of human waste.	Composting is a waste treatment technology used in circular sanitation designs that may mitigate GHG emissions relative to other waste fates, such as anaerobic pit latrines. Off-site composting presents a range of operational decisions that can impact GHG emissions. Specifically, pile management options that alter drainage, aeration or the use of bulking materials may reduce methane emissions or may increase nitrous oxide emissions (i.e., emissions swapping). The production of compost that can be sold as an agricultural organic amendment to enhance crop growth and soil fertility may represent another advantage (McNicol et al. 2020). On the other hand, in low-resource settings, human pathogen hazards can constrain management options.	MP: ★★★ One recent study shows that methane emissions during off-site composting of human waste are one to two orders of magnitude smaller than IPCC values for other excreta collection, treatment, and disposal processes (McNicol et al, 2020). This study also shows that, at local scales, the climate change mitigation potential is 126 kg CO_2 equivalent per capita per year for slum residents whose waste is composted. If scaled to cover all slum populations in the world, composting could mitigate 3.97 teragrammes of methane per year, representing 13-44% of sanitation sector methane emissions (McNicol et al. 2020).
Enhance the capture of methane from on-site sanitation through household biogas digesters.	Biogas produced from human excreta provides a renewable and clean-burning energy source. However, there is a high risk of significant leakage from poorly maintained systems, which may negate the mitigation potential (Bruun et al. 2014). Adoption of biogas may also be limited by the lack of a reliable supply of manure to feed the system, and possible failure in cold climates (Hou et al. 2017). Other barriers include the need for technical improvements, lack of social acceptance, and high investment costs (Garfí et al. 2016).	MP: ★★ Small-scale biogas digesters can help reduce global warming impacts if used appropriately. For instance, one study shows that when the biogas is used as a fuel for cooking, the mitigation potential will be reduced by 83% compared with the traditional wood biomass cooking system. In addition, the digestate can be used as a nutrient-rich fertilizer substituting more costly inorganic fertilizers, with no global warming potential impact (Rahman et al. 2017). However, if used inappropriately, the proliferation of biogas digesters could contribute significantly to global emissions of methane. More specifically, Bruun et al (2014) shows that methane emissions from the inlets and outlets of small-scale biogas digesters, from leaks and from intentional releases, are likely to be substantial because of poor maintenance and poor biogas handling. In many cases, the global warming impact of this methane could be greater than the impacts avoided by the replacement of other fuels for cooking and other purposes.

4.3.1 Mitigation of GHG emissions through optimized process selection and operational conditions of wastewater and faecal sludge treatment and discharge

In wastewater and sludge treatment, nitrous oxide is produced primarily during nitrogen removal processes (nitrification-denitrification). The dominant production (90 per cent) occurs in the biological stage while the remaining portion is produced in grit chambers and sludge storage tanks (Campos et al. 2016). The produced liquid nitrous oxide is typically stripped, i.e., transferred from the liquid stream to the air in aerated parts of the treatment process. Stripping also occurs in non-aerated zones, but at much lower rates compared with the aerated compartments (US EPA, 2021).

Some identified operational conditions leading to increased nitrous oxide production include: a) low dissolved oxygen concentration in aerobic compartments and the presence of oxygen in anoxic compartments; b) occurrence of transient anoxic and aerobic conditions, and shifts in dissolved oxygen concentrations; c) high nitrite concentrations in both aerobic and anoxic compartments; d) low chemical oxygen demand (COD)[4] to nitrogen ratio in the anoxic compartments; and e) sudden shifts of pH and ammonia concentrations (Campos et al. 2016).

Regarding methane, approximately 1 per cent of the inflowing COD can be transformed to methane (Daelman et al. 2013). In the absence of oxygen, methane is released in sewers (Liu et al. 2015), in particular in case of long detention times of wastewater (Foley et al. 2010). However, most of the methane emissions in WWTPs are attributed to sludge handling processes. The sludge line with anaerobic digestion may be responsible for over 70 per cent of methane emissions from WWTPs, while the remaining portion originates from bioreactors in the main treatment line (Campos et al. 2016).

Campos et al. (2016) identified three possible approaches to reduce direct GHG emissions: a) minimization through the modification of operational conditions; b) prevention by applying new configurations and processes; and c) capture and treatment of the gaseous streams containing GHGs. Currently, the last approach does not appear feasible due to high capital costs.

In existing WWTPs, changing the operational conditions appears to be the most economical approach to mitigate GHG emissions without deterioration of the required effluent quality. This is carried out mainly by aeration control, feed scheme optimization, or process optimization (Duan et al. 2021). For instance, the direct nitrous oxide emissions can be reduced by adjusting the conditions in the biological stage of WWTPs. Specific measures include the variable (step) aeration mode, the distribution of the return activated sludge between different compartments, controlling the dissolved oxygen concentrations in aerobic compartments and mixed liquor recirculations, and changing the operational mode (length of phases) in a sequencing batch reactor (Zaborowska et al. 2019). Even though nitrous oxide mitigation alternatives have been well recognized, Duan et al. (2021) identified five critical challenges for wider implementation of nitrous oxide mitigation strategies, including quantification methods of nitrous oxide emissions, reliable prediction models, risk assessment for WWTPs, the role of decentralized systems, and novel strategies promoting nitrous oxide reduction pathways (especially full denitrification). Regarding methane, emissions can be minimized effectively by covering sludge thickeners and other tanks storing sewage sludges. Then, the captured methane, instead of being cleaned, can be burned together with the biogas generated in the sludge anaerobic digester.

Despite being the most efficient in terms of cost, a change of operational conditions of WWTPs to reduce GHG emissions is not always possible due to the operational limitations of the installed units (e.g., the type of treatment technology, the volume of the reactor, effluent requirements, etc.). In consequence, most of the efforts to improve WWTP performance are being focused currently on prevention strategies, including aspects related to reduction of energy consumption, minimization of sludge production, and maximization of the amount and quality of biogas generated (Campos et al. 2016). More specifically, the energy consumption goal could be achieved by maximizing the anaerobic pathway for organic matter removal and using process alternatives for nitrification-denitrification (e.g., microalgae reactors or anammox-based systems). The drawbacks of this solution include the large area required for the microalgae reactors, the potential instability of the anammox process in the main treatment line, and the increased risk of high GHG emissions during the de-ammonification (partial nitrification + anammox) process (Vasilaki et al. 2019; Li et al. 2020).

4.3.2 Mitigation of GHG emissions through expanding wastewater collection and treatment, including decentralized sanitation solutions

As previously mentioned, a significant proportion of the wastewater produced globally is not treated. Available estimates are highly uncertain. On one hand, among the 42 countries and territories reporting on total wastewater generation and treatment in 2015, only 32 per cent of wastewater flows were subject to some form of treatment. On the other hand, an estimated 56 per cent of wastewater generated by households in 2020 was safely treated, according to data from 128 countries and territories (UN Habitat and WHO, 2021). These values are consistent with those reported by Jones et al. (2021), which indicate that approximately 63 per cent of globally produced wastewater is collected, with approximately 84 per cent of the collected wastewater undergoing a treatment process. These data, however,

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4. The chemical oxygen demand (COD) is the amount of oxygen needed to oxidise the organic matter present in water. The biochemical oxygen demand (BOD) represents the amount of dissolved oxygen consumed by biological organisms when they decompose organic matter in water.

mask significant regional disparities. On average, high-income countries treat about 70 per cent of the municipal and industrial wastewater they generate (Sato et al. 2013). In the EU, approximately 95 per cent of urban wastewater is collected, with more than 85 per cent meeting the stringent treatment requirements of the Urban Wastewater Directive (EEC 91/271/). However, the wastewater treatment ratio drops to 38 per cent in upper-middle-income countries and to 8 per cent in low-income countries (Sato et al. 2013).

In the absence of wastewater collection and treatment services, the expansion of decentralized sanitation solutions is imperative for the 1.69 billion people who currently lack basic sanitation services (WHO 2021). In this regard, Sustainable Development Goal (SDG) targets 6.2 and 6.3 represent an urgent call for action by all countries to provide adequate and equitable sanitation and hygiene for all, also ending open defecation, and to halve the proportion of untreated wastewater discharged into water bodies (United Nations General Assembly, 2015). The extension of wastewater and faecal sludge treatment through WWTPs and decentralized sanitation solutions to meet these targets should be viewed as an opportunity to significantly reduce direct GHG emissions. However, more evidence is needed to understand which low-cost sanitation solutions enable the most effective approaches to mitigating climate change, with a view to optimizing the entire faecal sludge management service chain, from the collection and transport of sludge to the final end-use or disposal of treated sludge.

Therefore, simpler mitigation measures to improve how sanitation services are designed, planned, and managed should be explored and implemented, such as enhanced design for septic tanks or lined pits, or appropriate operational or management solutions with a focus on the energy use and GHG production (WHO 2019). For instance, in on-site sanitation systems, long detention times for faecal sludge increase methane formation. In this regard, Reid et al (2014) found that methane emissions can be reduced by using aerobic decomposition, which can be achieved most simply by digging shallow pits that remain above the water table (which is also preferable for limiting groundwater pollution), or through the use of well-maintained composting toilets. Composting toilets separate liquid and solid waste and, with proper maintenance, the solids decompose aerobically to a nutrient-rich compost within a few months (also providing an opportunity for nutrient recycling). Small-scale biogas digesters that capture anaerobically produced methane before it is released to the atmosphere are another potential mitigation option (Reid et al. 2014). They generate biogas from human excreta and manure, and burn it as an energy source for household use, which can also serve as an alternative to collecting wood for burning (and reduce deforestation). As alerted by Bruun et al (2014) however, poor maintenance and poor biogas handling can partially or totally negate this mitigation potential. The International Energy Agency (IEA) estimates that the conversion of uncollected and untreated waste into cooking fuel for all people without access to clean sanitation would be enough to supply 60–180 million households (IEA 2018).

The future contribution of pit latrine and other decentralized sanitation solutions to methane emissions depends on the spread of these solutions in underserved areas, particularly in South Asia and sub-Saharan Africa. Recent statistics show that pit latrine users are expected to increase, mainly due to population growth (WHO 2021). It is therefore important to recognize both the global climate impact of pit latrine emissions and the availability of appropriate on-site mitigation measures. This would highlight potential synergies between water and sanitation development and GHG mitigation efforts. Before recommending specific mitigation actions, however, it is critical to characterize the climate change mitigation potential of decentralized sanitation systems with greater certainty (Reid et al. 2014).

4.4 Mitigation actions to reduce indirect GHG emissions from drinking water and sanitation

The withdrawal, treatment, and distribution of water as well as the collection, treatment, and disposal of faecal sludge and wastewater require a large amount of energy, which is associated with carbon emissions. Table 4.2 lists a number of mitigation actions to reduce, measure, and report indirect GHG emissions from drinking water and sanitation. Improved energy efficiency and the use of renewable energy, among others, can significantly decrease indirect CO_2 emissions from water and wastewater management, as well as reducing energy costs. In addition, it is crucial to measure and report emission reductions from these actions to contribute formally to mitigation objectives.

Table 4.2. Overview of potential mitigation action to reduce indirect GHG release from drinking water and sanitation systems (by reducing energy use)

★★★★ High mitigation potential due to highly efficient energy-saving measure and high level of scalability;
★★★ Medium to high mitigation potential due to highly efficient energy-saving measure but not easy to scale-up;
★★ Medium mitigation potential due to less efficient energy-saving measure;
★ Low mitigation potential due to low energy savings.

MITIGATION ACTION	PROS, CONS, AND CAVEATS	MITIGATION POTENTIAL (MP)
Conduct energy audits or life-cycle assessments (LCAs).	Energy audits allow for systematic identification of areas of inefficiency, also providing direction for energy-saving opportunities or energy conservation measures. LCAs enable the selection and prioritization of the best technologies and management models available.	MP: ★★★ In Western Australia, an LCA concluded that GHG emissions from electrodialysis desalination water treatment plants were more than six times higher than groundwater or surface water treatment plants due to energy-intensive treatment processes (Biswas and Yek 2016).
Introduce advanced aeration control systems.	Increased aeration efficiency refers to the improved oxygen transfer or to the decreased energy consumption per transferred unit of oxygen in the aerobic biological reactor. Aeration control systems can save considerable amounts of energy by quickly adjusting the operational conditions within the reactor. However, low oxygen levels through decreased aeration intensity may increase nitrous oxide production (Sweetapple et al. 2014)	MP: ★★★★ One case study from a Swedish WWTP showed that energy consumption decreased by 15% in the aeration process by improving aeration control strategy. It also helped deliver a better oxygen distribution, which led to higher sludge quality (Jonasson 2007).
Enhance pumping operations.	Pump stations upgrades, together with variable speed systems, can represent significant energy savings and reduction of GHG emissions. In addition, variable speed pumps can lower operation and maintenance requirements, if applied correctly.	MP: ★★★★ The Miyahuna utility in Madaba, Jordan, reduced GHG emissions in a water supply system by more than one third through the exchange of pumps and use of variable frequency drives. The utility also experienced a significant reduction in energy costs (Kerres et al. 2022).
Improve faecal sludge management.	The optimization of the entire faecal sludge management service chain (collection, transport, treatment, and disposal of sludge) provides a range of opportunities to reduce energy consumption. It also enhances resource recovery options. However, lack of accurate data often prevents the identification of the most efficient solutions.	MP: ★★★ A case study examining emissions across the entire sanitation chain in Kampala, Uganda, showed large emissions associated with long periods of storage of faecal waste in sealed anaerobic tanks (49%), discharge from tanks and pits direct to open drains (4%), illegal dumping of faecal waste (2%), leakage from sewers (6%), wastewater bypassing treatment (7%) and uncollected methane emissions at treatment plants (31%). Overall sanitation produced 189 kilotons CO_2 equivalent per year, which may constitute more than half of the total city-level emissions in Kampala (Johnson et al. 2022). This demonstrates high potential for mitigation through better management of pits and tanks storing faecal sludge.

MITIGATION ACTION	PROS, CONS, AND CAVEATS	MITIGATION POTENTIAL (MP)
Implement Nature-based Solutions (NbS).	Besides improvement of water quality, other possible co-benefits of NbS include increasing biodiversity, providing recreational areas and social well-being through green spaces; improving urban microclimates; flood and storm peak mitigation; biomass production; and enabling water reuse. NbS can therefore tackle the climate and biodiversity crisis while also contributing to sustainable development. On the other hand, NbS generally require more land than conventional systems (e.g., activated sludge). In addition, scaling up NbS first requires accurate assessment of GHG emissions.	MP: ★★★ In a compilation of case studies, Cross et al. (2021) provides evidence on the use of NbS for improved sanitation, with an emphasis on the co-benefits that these technologies can provide to both people and ecosystems, such as high treatment performance, high water reuse, or reduction of potent GHGs such as methane and nitrous oxide. Reciprocating (tidal-flow) treatment wetlands create aerobic, anoxic, and anaerobic environments within a treatment unit. The sequential aerobic/anoxic environments significantly improve removal of BOD_5, suspended solids, turbidity, ammonia, nitrate, and methane. Specifically, methane emissions can be consistently reduced by an average of 95% compared with adjacent anaerobic lagoon treatment. In addition, reciprocation has demonstrated energy efficiency and significant reductions in noxious odours such as hydrogen sulphide (Cross et al. 2021).
Reduce non-revenue water (i.e., water that has been produced and is "lost" before it reaches the customer).	It has been estimated that reducing the current level of non-revenue water in low-income countries by half appears a realistic target (Kingdom et al. 2006). This reduction could generate additional financial resources for the sector while significantly improving the energy efficiency and overall performance of water utilities. However, utilities often lack the governance, autonomy, accountability, and technical and managerial skills to effectively manage water losses.	MP: ★★★★ In Christchurch, New Zealand, significant efforts have been made since 1996 to manage non-revenue water with the aim to protect aquifers and thereby avoid the need to access different sources of water that require different types of treatment to meet acceptable quality standards. Initial work established techniques for surveying the losses in the system, and designed and constructed structures that would measure flow rates at night (when water consumption is lowest). To measure minimum night flows and non-revenue water, Christchurch's reticulation network was temporarily isolated into approximately 200 sub-zones by closing valves so there was only one single feed into a zone at which point the night flow was measured. The council surveyed approximately 40 zones per year using night flow testing and then carried out leak detection work. It took approximately five years to survey the entire city. This programme needs to be ongoing as water loss reduction work is a continuous effort, with the next step being the creation of permanent district metering areas.
Achieve energy neutrality through energy recovery.	Many possible solutions can be implemented for both reducing energy consumption and increasing renewable energy production in the WWTPs.	MP: ★★★ The As-Samra Wastewater Treatment Plant in Jordan has been developed in phases to increase energy recovery and water reuse. Since Phase 1, completed in 2008, the generation of renewable energy from the sludge treatment process provides 80% of the plant's power.

MITIGATION ACTION	PROS, CONS, AND CAVEATS	MITIGATION POTENTIAL (MP)
Increase use of renewable energy.	Besides the positive impact on climate change, increased use of renewable energy helps address two major challenges in the water and sanitation sector: the cost of maintaining operations and the degree to which delivery of water services depends on a steady supply of energy from utility companies. As an added bonus, solar power is also instrumental in solar irradiation, a water treatment method that eliminates a wide selection of chemicals and microorganisms, without producing harmful by-products.	MP: ★★★★ Biswas and Yek (2016) carried out a life-cycle assessment to calculate the carbon footprint associated with different drinking water production options and to identify areas of production with high levels of GHG emissions. They found that by using 100% renewable energy, 97, 92 and 89% of GHG emissions could be reduced via wind turbines, photovoltaic, and biomass, respectively. Although solar and biomass were found to be less promising than wind for providing electricity for reducing GHG emissions, the consideration of 100% electricity generation from wind is challenging given its intermittent nature and potential availability.
Enhance desalination processes.	It is expected that more water will come from desalination in the future, especially in areas where no other natural supply of potable water exists or when there are long periods of drought. However, in addition to the high upfront investment costs, once operational, plants require huge amounts of energy. Energy costs account for one third to one half of the total cost of producing desalinated water. Therefore, the cost of producing water is greatly affected by changes in the price of energy. Brine disposal is another environmental problem that should be considered when installing a desalination plant.	MP: ★★ Elsaid et al (2020) conducted a study to discuss the mitigation and control strategies of the different environmental impacts of desalination processes, i.e., brine loaded with chemicals being discharged back to the environment, and GHGs being released to the atmosphere. Feed water source and quality, desalination technology, and energy source were found to have a substantial effect on the overall desalination environmental impact. Specifically, hybrid and emerging desalination systems, and utilization of renewable energies were found to substantially reduce the negative impacts of desalination. However, the study also found that incorporation of renewable energies is still at laboratory or pilot scales, and can only be used for small communities in remote locations. Therefore, use of clean or renewable energy sources need to be combined with high energy-efficiency desalination processes.

4.4.1 Mitigation of GHG emissions through energy efficiency improvement measures

IEA sees a huge potential for energy savings in the water and sanitation sector (IEA 2018). Opportunities for efficient energy use can be detected through an energy audit, while other techniques such as life-cycle assessments (LCA) can help identify the best water technology available. In this regard, mitigation options include:

- Enhance efficiency of aeration in aerobic wastewater treatment
- Improve pumping operations, including pump upgrades
- Implement sound faecal sludge management modalities
- Substitute energy-intensive treatment technologies with nature-based solutions.

In WWTPs, since aeration holds the biggest share of the total energy consumption (in most cases >50 per cent), novel aeration control strategies are the most promising operational measure for energy saving (Maktabifard et al. 2018). The improved aeration efficiency has significant potential for reducing emissions of GHGs. However, the trade-off between the cost of aeration and nitrous oxide emissions should be monitored carefully (Maktabifard et al. 2020; Sweetapple et al. 2014), with aeration control systems focusing on avoiding over-aeration while ensuring sufficient dissolved oxygen concentrations.

After aeration, pumping operations represent the second most important energy consumption at WWTPs (Saghafi et al. 2016). It has been estimated that electric motors can account for 90 per cent of the electric energy consumption of mechanical devices in a WWTP (Water Environment Federation 2010). Similarly, pumps are often the largest consumers of energy in a drinking water system, with groundwater pumping requiring about seven times as much energy as withdrawal from surface water (IEA 2018). In total, for either surface or groundwater systems, pumping typically accounts for 90–99 per cent of energy consumption at a water system (US EPA 2013). Variable speed operation is often the most energy-efficient flow control method for pumping systems, as it can result in better process control, smoother operation, and reduced maintenance costs for the pumping station (Ahonen et al. 2015).

Several other measures can be undertaken to improve the energy balance of water and wastewater treatment and transportation, including reduction of physical water losses and maintenance of pipes, technological upgrades of sludge management, digitalization, sensors, process controls, etc. (Kerres et al, 2022). Previous solutions to reduce energy consumption and foster energy efficiency, however, have been designed for and in high-income countries, and low-income countries might require customized, different, or new solutions (Larsen et al. 2016). For instance, faecal sludge management offers a huge potential for mitigation, such as the optimization of energy and fuel consumption for the emptying of septic tanks and pit latrines by an upgrade of the vacuum pumps, improved transport routes and shorter distances to the treatment plant, and a more efficient organization of emptying services. Nature-based solutions, such as constructed wetlands, can also offer the potential to substitute energy-intensive treatment technologies. Yet, the mitigation potential of nature-based solutions has yet to be unleashed and, for their wider implementation, better and more accurate assessment of GHG emissions will be needed (Cross et al. 2021).

4.4.2 Mitigation of GHG emissions through water efficiency improvement measures

Linked to energy efficiency, another area with significant mitigation potential relates to water efficiency through reduction of water losses and unnecessary water consumption. In this regard, one key performance indicator to measure efficient operation of water utilities refers to non-revenue water (NRW), which can occur through physical losses from leaking and broken pipes, commercial losses caused by inaccurate metering, poor data gathering, illegal connections and theft, or unbilled authorized consumption (e.g., water used for firefighting and water provided for free to certain consumer groups).

NRW is one of the most persistent problems in municipal water systems. In a recent study, the global volume of NRW has been estimated at 346 million cubic metres per day or 126 billion cubic metres per year (Liemberger and Wyatt, 2018). This is equivalent to 30 per cent of water system input volumes across the world, and the total cost of such losses can be up to USD 39 billion per year. The problem varies by region. The lowest NRW levels (36 litres per capita per day) can be found in Australia and New Zealand, due to the extensive water loss reduction efforts made to cope with the long droughts that have occurred in Australia during the past decade. The average level of NRW in Latin America and the Caribbean is 121 litres per capita per day, while in Europe and the United States it is 50 and 119 litres per capita per day, respectively (Liemberger and Wyatt 2018). Another study assessing the performance of urban water utilities in Africa estimates that NRW losses can range between 20 and 40 per cent (van den Berg and Danilenko 2017).

Important drivers are pushing for NRW reduction besides the reduction of GHG emissions. These are related mainly to: a) promoting utilities' financial sustainability through cost recovery; b) securing water availability; and c) managing water stress. Therefore, the benefits of addressing NRW relate not only to environmental benefits through reduced impact on the environment and less energy consumption, but also to important economic and financial benefits that result from the reduction of the volume of water treated and/or the reduction of costs related to operation and maintenance (O&M).

4.4.3 Mitigation of GHG emissions through deployment of renewable energy

The replacement of fossil energy sources with renewable energy can significantly reduce emissions in water and wastewater management, while also lowering energy costs and reducing dependence on fuel availability. Options include energy generated by photovoltaics and wind, and small hydropower solutions (Olsson 2018).

In addition, as they are usually connected to an existing electricity grid, utilities that generate energy from renewable sources can feed excess energy into that grid. Facilities not connected to an electricity grid can make use of standalone renewable solutions as an alternative to carbon-intensive options such as diesel. This might be the case in remote rural areas, where most water pumping is currently powered by diesel.

4.4.4 Mitigation of GHG emissions through enhanced desalination processes

Desalinated seawater and brackish water contribute to less than 1 per cent of the international water supply. However, the share of electricity for desalination was estimated at about 26 per cent of the water sector's electricity use in 2016 (IEA 2018). In the Middle East, where almost half of the global desalination is installed, more than a quarter of the sector's energy consumption is used for desalination, mostly through natural gas and oil, with consequent implications for CO_2 emissions.

Desalination is an energy-intensive process, although the amount of energy required depends on the technology used, the capacity of the desalination plant (small, medium, or large), and the type of feed water (the desalination of brackish water requires only about one tenth of the energy needed for seawater desalination). In addition, the use of renewable energies can significantly decrease energy consumption and related GHG emissions. While research in desalination and renewables is ongoing, it seems that membrane-based facilities connected to the electricity grid might be able to use excess electricity from renewable energies. Studies also suggest that renewables are currently working better with small-scale desalination schemes (Ahmadi et al. 2020).

4.4.5 Mitigation of GHG emissions through energy recovery

For the carbon embodied in the water and wastewater supply chains to become net zero, all key infrastructure and provisioning systems will need to be decarbonized (Seto et al. 2013). However, it has become increasingly evident that WWTPs worldwide have the potential to be energy-neutral or energy-positive facilities, where the energy needs of a treatment facility are satisfied entirely by self-generation, with the potential to produce more energy than needed through energy recovery improvements. Wastewater contains a significant amount of chemical, thermal, and hydrodynamic energy, which can be partially recovered. With the best available techniques, it is estimated that utilities can generate 50 per cent more electricity than they need (IEA 2018).[5] Wastewater is then valorized, enabling WWTPs to sell clean energy and recover the costs of treatment (IEA 2018). In turn, conversion of wastewater into bioenergy sources can reduce emissions if they replace certain sources, including fossil fuels. A few success stories have already been documented (Gu et al. 2017, Maktabifard et al. 2018, see Box 4.1).

The chemical energy, bound primarily in organic compounds (approximately 1–4 kilowatt hours per kilogramme COD), has the highest potential for efficient recovery by applying anaerobic digestion and biogas production coupled with combined heat and power engines or boilers. Different sludge pre-treatment methods (thermal hydrolysis, chemical pre-treatment, ultrasound/microwave, and hydrodynamic disintegration) can be used to increase the biogas production rate and efficiency.

The remaining electricity demand for complete energy neutrality could be covered mainly by organic waste co-digestion and application of renewable energy and heat recovery systems, although it is questionable whether external organic waste streams can account wholly for the WWTP energy balance. In addition, despite the high potential for increasing biogas production through co-digestion (up to 200 per cent), its possible negative

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[5] This potential does not apply only to large, centralized treatment plants.

Wind turbines providing electricity for the desalination plant at Costa Teguise, Lanzarote, Spain. Source: Shutterstock.

Box 4.1. Achieving energy neutrality in watstewater treatment plants in Europe

Gu et al. (2017) listed the full-scale energy-neutral and energy-positive WWTPs worldwide. Among the European case studies, two Austrian plants (Wolfgangsee-Ischl and Strass) are energy neutral. Wolfgangsee-Ischl WWTP produced on average approximately 21 kilowatt hours per population equivalent (kWh/PE) of electrical energy through biogas from anaerobic digesters and the number of the digesters exceeded the plant's electricity demand. Therefore, surplus electricity was sold to the grid. The total electricity consumed in Wolfgangsee-Ischl was 19 kWh/PE, of which 11 kWh/PE was consumed for aeration and mixing of the aeration tank, and the remaining 8 kWh/PE was consumed by other treatment processes.

The other successful case study in Austria is Strass WWTP. In that plant, 21 kWh/PE of electric energy was produced through biogas from anaerobic digestion of sludge. 'Combined heat and power', a system using the anaerobic digestion of sludge, is the technology most widely adopted in the existing energy self-sufficient WWTPs, including the Austrian case studies. The total electricity consumed in the Strass WWTP was 20 kWh/PE, of which 9 kWh/PE was consumed for aeration and mixing of the aeration tank, and the remaining 11 kWh/PE was consumed by other treatment processes. Together with the enhanced on-site electricity production, the WWTP reduced its energy consumption by 12 per cent after switching the previous conventional nitrification/denitrification process to a full-scale novel process of deammonification (partial nitration – anammox).

impact should not be ignored. While energy recovery via biogas production can decrease indirect GHG emissions, there may be additional GHG losses during anaerobic digestion and release with incomplete biogas combustion (Maktabifard et al. 2020). The CO_2 emitted indirectly due to the energy consumed by wastewater and sludge processes (if renewable energies are not in place) can also be reduced by improving the energy efficiency of those processes.

IEA (2018) projects that if current typically centralized urban wastewater treatment technologies are expanded to meet SDG targets 6.2 and 6.3, the required electricity demands would increase by over an additional 680 terawatt hours (TWh) by 2030. This typical scenario would recover 6 per cent of electricity demand from energy production using wastewater. The range for improved performance is thus significant. If adopting more viable technologies (e.g., deployment of variable speed drives, more efficient compressors, better sludge management, etc.) energy efficiency could increase by 10 per cent, and energy generation could recover 30 per cent of the demand. Using the best available emerging technologies for all new wastewater facilities, the electricity demand could be reduced by approximately 30 per cent (to 480 TWh by 2030) and, as mentioned above, energy recovery from wastewater could be increased to 150 per cent. Depending on the source of energy, the reduction in energy use can translate into the reduction of GHG emissions and significant financial benefits through decreased operation and maintenance costs.

4.5 Gaps in global climate policy and financing

4.5.1 WASH is not well represented in national climate policies and strategies

Despite the importance of drinking water and sanitation for climate action, the sanitation sector continues to be poorly represented in climate policy and climate finance. One key policy instrument where this lack is evident is within the Nationally Determined Contributions (NDCs). The NDCs outline the steps or commitments countries are taking to reduce emissions, as well as their adaptation actions. A detailed analysis of the first round of SDG 6-related NDCs (approximately 2015–2018), showed that only 2 per cent of concrete activities included in these NDCs deal with sanitation access, while for wastewater, only 3 per cent of SDG-related NDC activities were identified (see Figure 4.3, Dickin et al. 2020). These included activities in both adaptation and mitigation sections, but mainly in adaptation. This analysis also found that no sanitation-related mitigation activities are included in the NDCs by China, India, Indonesia, or USA, all of which are making large contributions to emissions from wastewater. Instead, identified activities were

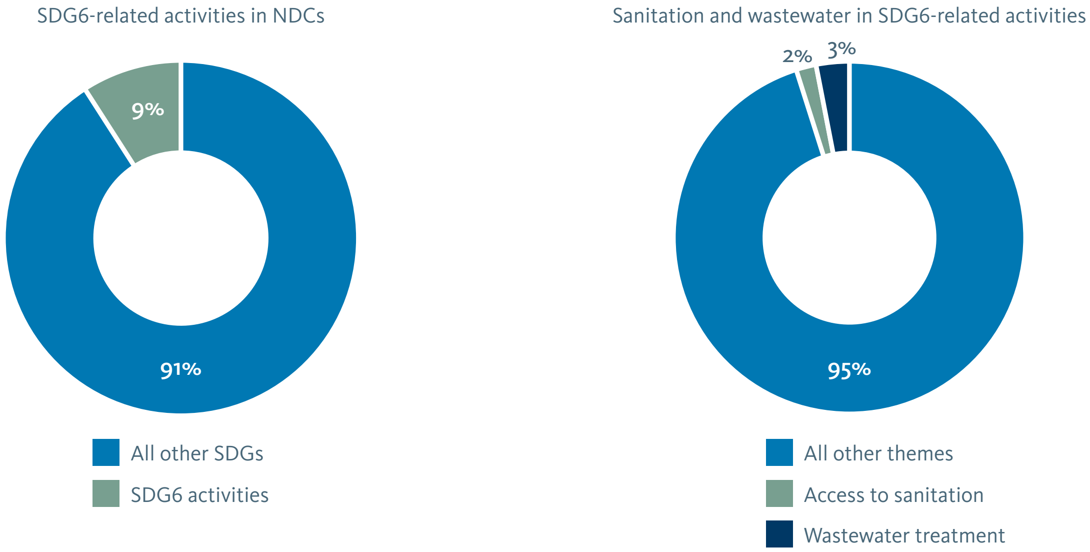

Figure 4.3. SDG-NDC connections: a) 630 out of 6,900 activities (9 per cent) were related to SDG 6 in the first round of NDCs; b) within SDG 6-related activities, 2 per cent were linked to access to sanitation and 3 per cent to wastewater treatment. Source: Dickin et al. (2020).

mostly from low- to middle-income countries in the Middle East and North Africa, and sub-Saharan Africa regions. Recent analysis of enhanced NDCs prepared by non-Annex 1 parties released in the two years prior to the beginning of 2022 noted an increase in the inclusion of water supply, sanitation, and hygiene measures in adaptation sections (SIWI/GIZ NDC study (forthcoming). For example, 43 per cent of non-Annex 1 countries included sanitation measures in adaptation sections, but direct water mitigation measures in WASH remain limited.

4.5.2 Climate finance offers an opportunity for WASH-related climate action

The Climate Policy Initiative has been compiling global estimates of climate finance for mitigation and adaptation since 2011, disaggregating data by sector and type of finance instrument (public and private, domestic and international). These estimates show that the water sector (including sanitation) receives a substantial share of committed adaptation-related finance (43 per cent of the annual total since 2011, on average) with funding standing at USD 19 billion in 2020 for water and wastewater management. Water and sanitation-focused mitigation-related finance is growing but is more modest at USD 1 billion in 2020 for water and wastewater combined, representing only 0.1 per cent of the total global climate finance for mitigation. An additional USD 2 billion goes to both adaptation and mitigation combined. Since the total global climate finance amount allocated to mitigation is far greater than that allocated to adaptation, the total share of climate finance for water and sanitation overall is approximately 3.5 per cent (CPI 2021). Complementary climate finance data is provided by the OECD (see Box 4.2).

However, these aggregates mask sharp disparities between water supply and sanitation, and between centralized and decentralized systems. Dickin et al (2020) shows, for instance, that projects related to water supply and sanitation with climate change as a main objective often fail to incorporate a specific sanitation or wastewater element, with only 3 per cent of climate-related finance for the water supply and sanitation sector targeting mitigation and adaptation related to sanitation.

4.6 Gaps in global data and knowledge

Data and information on GHG emissions from water supply and sanitation is limited and associated with high levels of uncertainty. In part, this knowledge gap hampers effective integration of WASH in climate policies and mitigation strategies and, in turn, presents a challenge to the availability of climate finance, as already mentioned above.

Box 4.2. Climate-related development finance in the water and sanitation sector, based on development finance data

Examining climate-related official development assistance (ODA) data for water and sanitation, as tracked by the Organisation for Economic Co-operation and Development (OECD) DAC, shows that 13.7 per cent of all development finance flows tagged as climate related from 2000 to 2019 was allocated to water- and sanitation-related fields. This specifically comprises 9.7 per cent of the total in the case of adaptation-related flows, and 4 per cent of the total in the case of mitigation-related flows (Figure 4.4).

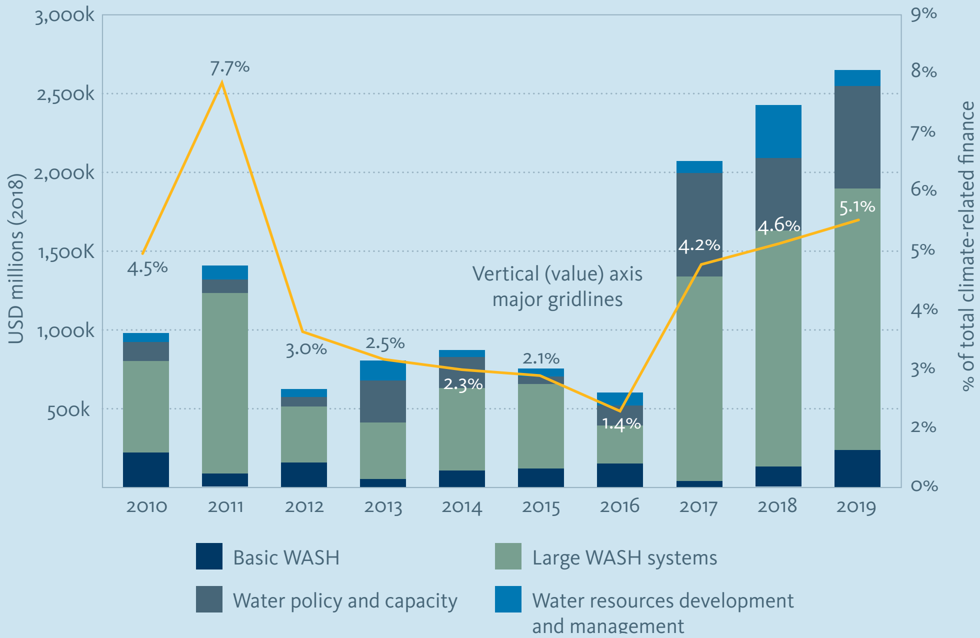

Figure 4.4. Climate-related development finance for mitigation to water subsectors (2000–2019). Source: OECD (2022).

OECD tracks 11 sub-sectors under the WASH sector. To aid interpretation, however, the data has been grouped into four main categories: basic WASH systems, large WASH systems, water policy and capacity, and water resources development and management. Focusing on mitigation, Figure 4.4 shows the proportion of climate-related finance allocated to these categories between 2010 and 2019 (yellow line). The share tagged as climate related for mitigation decreased from 2011 to 2016, to a low of 1.4 per cent, then increased to 5.1 per cent in 2019.

The figure also illustrates the amount of climate-related development finance dedicated to each category. Large WASH systems historically represent the largest share (2.3 per cent of all climate-related finance for mitigation between 2010 and 2019), with water policy and capacity coming second at 0.7 per cent. Basic WASH has received the lowest share, at 0.4 per cent in total during the time period, decreasing from an average of 2.1 per cent in 2000–2009. As previously discussed, the global warming potential of providing safely managed sanitation for all cannot be neglected, and more resources should be mobilized based on GHG mitigation opportunities. Combined, basic WASH and large WASH systems have represented just 2.6 per cent of all climate-related finance for mitigation over the period 2010–2019. It is noted, however, that projects tagged as climate related can have multiple objectives, and that there is no discernible pattern of mitigation-focused finance going to sanitation as opposed to water supply (Calow et al. 2020).

Water utilities in many countries neither measure nor report their emissions, and Saunois et al. (2016) suggests that inventories for anthropogenic sources of methane in the waste sector might miss the mark by 20 to 30 per cent. This is due to the complexity of the processes influencing emissions, and inadequate reporting and accounting of contributions by type of source, as well as the absence of consistent measurements from different systems. Similarly, McNicol et al. (2020) states that GHG inventories and mitigation opportunities in water and sanitation are largely unknown due to the scarcity and variability of the data available from different water supply and sanitation systems. In this regard, data gaps and limitations in GHG accounting are not specific to a particular water supply or sanitation system, although knowledge has advanced more slowly regarding on-site sanitation, such as those associated with ecological sanitation.

If data collection is set as a priority in the international agenda, systems can include, by design, features to provide consistent measurement of emissions, making GHG accounting stronger across water supply and sanitation systems. In addition, water utilities can apply specific tools to strengthen assessment, monitoring, and reporting of GHG emissions, such as energy audits or the ECAM tool (Kerres et al, 2022, see Box 4.3). GHG emissions from water and wastewater management can then be regularly reported to the respective authorities based on the IPCC guidelines, as a necessary step to promote their inclusion in national GHG inventories. In this regard, the IPCC guidelines, which have been continuously updated (Eggleston et al. 2006; IPCC, 2019), provide an important mechanism in standardizing and guiding accounting throughout different sectors and allowing for comparison.[6] However, constraints to the advancement of knowledge related to different dimensions of sanitation system emissions and accounting can downplay the applicability of results in mitigation action.

For example, in the case of decentralized systems, there are uncertainties due to high levels of inadequate or missing data from local sources (Ryals et al. 2019; Huynh et al. 2021), the ways in which such information is organized in databases, and the application of emissions factors (González et al. 2019). This is primarily the case in low- and middle-income countries, where the informal nature of sanitation services delivery often hampers regular data collection and reporting. For on-site sanitation, direct measurements are scarce, not only in relation to containment but also to other steps of the sanitation chain, i.e., collection and emptying of faecal sludge, transportation, treatment, and end-use and disposal, making estimations from emissions factors even more limited (Mills et al. 2020; Reid et al. 2014). Therefore, understanding the quantity of GHG emissions from on-site sanitation and other decentralized solutions, and how these may vary with alternative design and management strategies, is crucial, also given the increasing number of people accessing these facilities in low- and middle-income countries.

Similarly, data gaps for centralized systems include lack of consideration of the organic fraction in different wastewater flows (Falk et al. 2013), methodological issues for estimation of nitrous oxide emissions, lack of consideration of operational conditions in relation to potential higher production and release of gases, and the application of emissions factors that are not always confirmed by direct measurements (Lahmouri et al. 2019). Another limitation refers to the inclusion of CO_2 from wastewater in the assessment. The IPCC guidelines have always considered these to be null, given they are usually derived from modern (biogenic) organic matter in human excreta or food waste, not accounting for the transfer of carbon to the atmosphere. However, recent work has contested such a premise, alleging the presence of fossil organic carbon in sewage, originating from cosmetics and pharmaceuticals for example. This has been recognized in the 2019 refinement of the guidelines, but not yet incorporated in its methodology. Similarly, the latest IPCC guidelines have produced other significant improvements, e.g., in relation to the measurement mechanisms concerning nitrous oxide emissions from domestic wastewater, even though large uncertainties are still associated with the provided default factors and assumptions.

Therefore, data collection and adequate reporting and accounting are still some of the biggest challenges for mitigation in the sector, hampering appropriate understanding of how emissions occur throughout different systems and processes.

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6. The IPCC guidelines for GHG emissions inventories do not include a water chapter. Instead, emissions from water and wastewater management are reported in volumes 2 (Energy) and 5 (Waste).

Box 4.3. User-friendly tools for analysis and continuous monitoring enable sustainable mitigation efforts

Accurate reporting on GHG emissions is becoming increasingly important and mandatory. To meet this demand, gain greater insight into the current emissions status, and identify areas where GHG emissions can be reduced, the **Energy Performance and Carbon Emissions Assessment and Monitoring** (ECAM) tool was developed by the Catalan Institute for Water Research within the scope of the Water and Wastewater Companies for Climate Mitigation (WaCCliM) project. WaCCliM is a joint initiative between the German Agency for International Cooperation and the International Water Association as part of the International Climate Initiative, financed by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection.

Using ECAM, water and wastewater utilities are assessing their energy use and GHG emissions by considering all components of the urban water cycle, from water supply to wastewater treatment, sludge management, and water reuse. ECAM follows the 2019 IPCC guidelines and requires data that are typically available from utilities in developing and emerging economies. Where data is not available, the tool generates estimates using information from international databases and examples of good practice. The results also allow utilities to identify priority areas for reducing emissions and seeking climate finance.

4.7 Conclusions, outlook, and recommendations

4.7.1 Conclusions

To respond to the question: Are we on the right track to mitigate the climate change effects of drinking water and sanitation? – the answer is: we are not yet making enough progress. A basic vicious cycle needs to be broken. First, there is a need to reduce uncertainty levels around GHG emissions and develop solid climate evidence, combining the best available data and information generated from enhanced monitoring and reporting processes with local knowledge and context. Second, climate evidence needs to be part of water and sanitation policy-making, strengthening the alignment of WASH and climate priorities in national policies. In turn, a demonstrated climate narrative should help position WASH to attract climate financing and new investments.

Therefore, although improved management of water and sanitation services represents a major opportunity for climate mitigation, several obstacles and bottlenecks discourage climate decision-makers from prioritizing and investing in WASH. These include the following:

Lack of data hampers evidence-based climate action. Critical information and reporting gaps lead to probable underestimation of the GHGs released in the water supply and sanitation chain. Various challenges hamper data collection and adequate accounting of these emissions, including limited water quality monitoring, inadequate emission measurements by type of source (particularly from on-site and decentralized sanitation systems), limited GHG measurements in water and wastewater facilities despite available digital tools, and certain ambiguities in the IPCC guidelines for estimating emissions. Global data reporting gaps result in these emissions not being included in national GHG accounting, and actions to reduce GHG emissions are not adequately incentivized.

At the policy level, **poor representation of WASH in the climate policy debate** suggests that national policy-makers involved in setting climate goals do not appreciate the role of WASH, particularly sanitation, in climate action. At the same time, WASH actors have often been reluctant to develop a narrative that describes how climate change affects service provision and to disseminate this narrative beyond the WASH domain. Neither have they sufficiently documented the potential contribution of GHG from water and sanitation systems to climate change.

In terms of finance, **WASH projects rarely estimate their potential for emissions reduction** by, for example, outlining how GHG emissions will be cut and energy efficiency enhanced. A demonstrated climate narrative should be the basis for identifying climate opportunities and promoting WASH interventions that not only consider adaptation solutions but also better integrate the mitigation potential.

4.7.2 Recommendations

Against these challenges, the recommendations below suggest the way forward**.**

Increase evidence: More and better data and reporting of actual GHG emissions from water and sanitation infrastructure needs to be prioritized by mobilizing political will at the institutional level. Different pathways should be explored. Available guidance and accounting tools for monitoring and reporting of GHG emissions from water utilities such as ECAM need to be scaled up via capacity-building and training as a necessary step to advocate for their inclusion in national GHG inventories. In addition, reporting guidelines for water utilities should be standardized and, in the best case, backed by an international authority such as IPCC, including the choice of a functional unit for this assessment. Carbon footprint assessment studies and energy audits can also provide new and better evidence to enhance accounting and reduce uncertainty levels of GHG emissions across different water supply and sanitation systems and, in turn, improve the reporting guidelines. Finally, research studies can provide new evidence on the actual contribution of different decentralized solutions in terms of GHG emissions, e.g., including emissions not only at the point of delivery but also along the whole water supply and sanitation chain.

Enhance policy-making: Apart from documenting the potential contribution of water and sanitation systems to climate change through GHG emissions, context-specific evidence of the impact of climate on the delivery of WASH services needs to be strengthened. Available knowledge and evidence need to inform climate policies and strategies, thus linking to the broader climate debate beyond WASH. The formulation of response plans and interventions should be promoted, clearly showing the mitigation potential. Then, the actual implementation of policies, plans, and strategies needs to be regularly monitored, identifying bottlenecks that constrain progress.

Incentivize investment: Climate finance provides an opportunity to expand and enhance drinking water and sanitation management at a large scale through climate-resilient WASH solutions. A significant proportion of wastewater globally is currently not treated or only partially treated and would emit much less GHG if proper collection and treatment systems were in place. Similarly, mitigation efforts should be aligned with the provision of safely managed sanitation for the millions of people who currently lack this service. With an urgency to enhance delivery of WASH services while reducing emissions, there is a need to promote greater opportunities for climate finance to complement development finance, particularly in the sanitation sector. In addition, one recent study suggests that much of the climate-related finance fails to align with critical needs (WaterAid 2021). A shift in financing priorities could therefore be recommended from a human rights and climate justice perspective to ensure that the most efficient, effective, and equitable measures within the water and sanitation sector are identified and implemented. In this regard, the priority in low-income contexts should be to secure access to basic services, with mitigation opportunities considered in the context of win-win solutions.

Gather momentum: To achieve impact at scale, the establishment of climate platforms is the key to strengthening cooperation among climate and WASH stakeholders and enhancing action on mitigation solutions. These platforms should provide access and stimulate exchange of information, evidence, and guidance intended to inform the development of climate mitigation strategies and plans at the local, national, and international scales. At the same time, although knowledge, technologies, and infrastructure exist for energy-efficient and low climate impact water and wastewater processes, more guidance and improved design standards are needed to promote low GHG interventions that can be scaled up through investment, capacity building, and training.

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CHAPTER 5

Mitigation measures in freshwater ecosystems

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Chapter 5 Contents

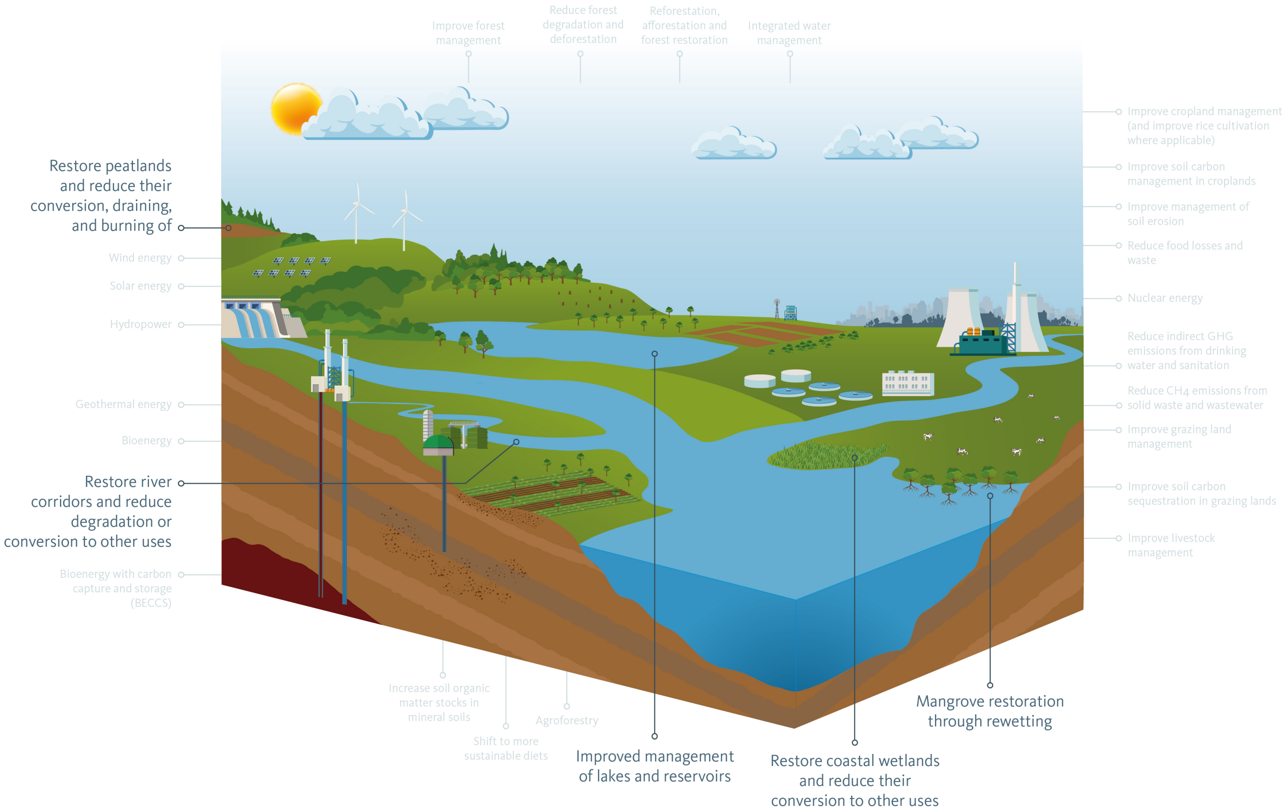

Figure 5.0. Mitigation measures in inland freshwater ecosystems and freshwater-dependent coastal and marine ecosystem. Source: SIWI.

Highlights

- Freshwater ecosystems can function as greenhouse gas (GHG) sources and sinks based on their environmental state and management. While restoration of wetlands and floodplains is an effective measure for mitigation, stronger priority should be given to protecting existing natural wetlands and floodplains to avoid additional GHG release. Freshwater ecosystems, such as peatlands, marshes, swamps, lakes, streams, rivers, and tidal wetlands, have high potential for mitigation when managed well, but can contribute additional emissions when managed poorly. Land use, surrounding vegetation, pollution, human activities, hydrologic regime, and climate can influence the emissions profile of freshwater ecosystems. Mitigation-relevant data and research on rivers, lakes, and dams is scarce, while wetlands are more acknowledged and researched.
- It is important to promote a concerted effort nationally and internationally to account for the GHG emissions from freshwater ecosystems. In addition to 'blue carbon' ecosystems (BCE), which include freshwater-dependent coastal and marine systems, the emission reduction potential of freshwater ecosystems needs to be more commonly included as a measure to reduce atmospheric GHG emissions alongside sectors outside of land use, such as energy and transport.
- The potential (or use) of catchment and coastal zone policies, programmes, and investments to support effective and sustainable emission reduction strategies needs to be recognized and adopted. GHG production in aquatic systems is driven by nutrient and organic carbon inputs from watersheds. Effective emission reduction strategies may entail integrated approaches for land management and regenerative agriculture, restricting nutrient loading (including improved wastewater treatment capacities), and maintaining and improving ecohydrological connections.
- Natural solution schemes (both nature-based solutions and green-grey infrastructure) need to include the full range of ecosystem services, alongside carbon sequestration, to reduce the risk of maladaptation. Carbon sequestration is only one of many valuable services provided by aquatic ecosystems. There are multiple direct and indirect co-benefits, such as flood risk management, biodiversity recovery, sustainable communities and livelihoods, and water quality improvement that come with watershed-scale aquatic ecosystem management. These benefits need to be accounted for while integrating emissions reduction targets in the Nationally Determined Contributions.
- Net emissions reduction goals and opportunities need to be given greater emphasis within broad water resources management strategies. There is also a need for financing mechanisms and tools to monitor and reduce emissions from freshwater ecosystems and BCE management at the local, regional, and national levels. Regulatory reform, capacity building, and better data on aquatic environments are needed to further opportunities and materialize implementation.

5.1 Introduction

Freshwater ecosystems such as wetlands, rivers, and lakes are linked intimately with climate mitigation since aquatic environments can act as both greenhouse gas (GHG) sources and sinks based on their environmental conditions and management practices. However, the role of freshwater ecosystems in achieving climate mitigation targets has yet to be acknowledged to the extent reflecting their potential. Freshwater ecosystems can be sources of all three major GHGs (carbon dioxide or CO_2, methane, and nitrous oxide) and eliminating emissions entirely from these systems is unrealistic due to their natural processes. But their carbon storage capacity, for which they have high potential, can be enhanced and emissions from these sources can be reduced to achieve net emissions reduction. In reviewing the mitigation potential of different freshwater ecosystems, this chapter makes a clear case for the adoption of land- and watershed-scale policies across different aquatic environments for effective and sustainable strategies that support and enhance the role of freshwater ecosystems in mitigating climate change.

'Blue carbon' ecosystems (BCE), particularly mangrove swamps, are commonly acknowledged for their mitigation potential and have received much greater attention than inland freshwater ecosystems in this regard (IPCC 2014). Hence, in this chapter we focus on freshwater ecosystems (wetlands, lakes, reservoirs, and rivers) and freshwater-dependent coastal and marine systems. This chapter takes a 'problem-cause-solution' approach to addressing freshwater ecosystem-based climate change mitigation. It discusses under what circumstances the long-term carbon sinks, i.e., the freshwater ecosystems, become carbon sources and how to undo or minimize that shift to continue benefiting from the potential to sequester carbon. These mitigation measures come with substantial co-benefits and align with the Sustainable Development Goals, but their adoption might need to be tailored according to the local and regional context.

This chapter examines the mitigation potential and water-related risks of inland freshwater ecosystems and freshwater-dependent coastal and marine systems. Section 5.2 addresses relevant mitigation measures, which are categorized as wetlands, rivers, streams, lakes, and reservoirs. Section 5.3 examines trade-offs related to freshwater-based mitigation as well as co-benefits, more specifically the enhancement of ecosystem services through mitigation measures; climate change adaptation and resilience benefits from mitigation measures; and nature-based solutions associated with the mitigation measures. Current policy measures are explained in section 5.4. In 5.5, potential implications for governance are mapped, including inclusion in national policies, system-level approaches, and implications of future climate change and socio-economic change. Section 5.6 provides conclusions and an outlook for the future.

5.2 Mitigation potential of inland freshwater ecosystems and freshwater-dependent coastal and marine ecosystems

Depending on the management applied, wetlands can act as GHG sources or sinks (Hamdan and Wickland 2016). While emission, sink, and sequestration patterns are widely studied and understood for some wetlands, there is considerably less research on rivers and streams. Wetlands have high carbon sequestration potential, but when disturbed and drained they become sources of GHG emissions. While restoration can significantly reduce GHG emissions and may start carbon sequestration, restored wetlands might not return to the undisturbed natural conditions that allow high climate mitigation potential even within decades (Günther et al. 2020; Joosten 2015; Kreyling et al. 2021). Under the current climate change trajectory, wetlands require attention because they have high potential for mitigation when managed well and can contribute to additional emissions when managed poorly. This section elucidates the mitigation potential and measures based on existing knowledge (Table 5.1).

Table 5.1. Mitigation measures in inland ecosystems and freshwater-dependent coastal and marine systems addressed in this chapter.

MITIGATION MEASURE	MITIGATION POTENTIAL (GT CO_2-E/YEAR)
Reduce conversion, draining, and burning of peatlands	0.45–1.22
Reduce conversion of coastal wetlands (mangroves, seagrass, and marshes	0.11–2.25
Peatland restoration	0.15–0.81
Mangrove restoration through rewetting	0.07
Coastal wetland restoration	0.20–0.84
Reduced degradation or conversion of river corridors	–
River corridor restoration	–
Improved management of lakes and reservoirs	–

Note: includes data on climate mitigation potential when available in recent Intergovernmental Panel on Climate Change (IPCC) reports (IPCC 2019; IPCC 2022) in Gigatons of carbon dioxide equivalent per year (Gt CO_2-e/year)

5.2.1 Mitigation measures in wetlands

Conserving and restoring wetlands, including peatlands and coastal wetlands, is a critical climate mitigation strategy. Wetlands have among the highest stores of soil carbon in the biosphere, storing more than 30 per cent of the estimated global carbon emissions (Nahlik and Fennessy 2016). Despite covering about 7 per cent of the world's surface, wetlands are considered as the largest terrestrial carbon sinks due to their carbon sequestration capacity, both for a longer timescale in the past and their future potential (Mitsch and Gosselink 2015; Ramsar Convention on Wetlands 2018). The vegetation in marshes (minerotrophic wetlands dominated by herbaceous plants) and swamps (wetlands dominated by arboreal vegetation), through the process of photosynthesis, captures CO_2 and fixes it as organic matter in leaves, stems, and roots. Much of this organic matter eventually becomes incorporated into the soil. The saturated soils of wetlands have slower decomposition than those of dry soils. When plant productivity exceeds decomposition there is a net accumulation of carbon-rich soil. As a result, wetland soils sequester more carbon per unit volume than terrestrial soils (Bridgham et al. 2006; Kolka et al. 2018; Mazurczyk and Brooks 2018; Moomaw et al. 2018).

While natural wetlands are generally carbon sinks, drainage and other anthropogenic activities can make wetlands net sources of GHG instead. Moreover, although wetlands are considered as important sinks for CO_2, almost all freshwater wetlands emit methane, which has significantly higher global warming potential than CO_2. Since methane is split relatively quickly by oxidation in the atmosphere (while atmospheric CO_2 continues to be absorbed), the long-term carbon balance of intact peatlands is positive. In addition, there is a risk of large quantities of CO_2 and methane being released when temperatures are warming in frozen soils (permafrost) within Arctic and sub-Arctic regions, but the magnitude and timing of GHG emissions from these regions and their impact on climate change remain uncertain (Schuur et al. 2015).

Mitigating climate change can also have a positive impact on wetlands (Yuan at al. 2022). Altered hydrological regimes and more frequent or intense extreme weather events due to climate change will contribute to wetland degradation. Wetland loss and degradation increase GHG emissions to the atmosphere, leading to positive feedback on climate change. In fact, global GHG emissions from wetlands are projected to increase by up to 78 per cent under certain climatic conditions (with a doubling of atmospheric CO_2) (Gedney et al. 2019; Salimi et al. 2021). It is essential to address the climate change induced changes in wetland management to limit GHG emissions. When there is a higher rate of decomposition than of photosynthesis, wetlands emit CO_2 and decomposition depends mostly on thermal and hydrologic regimes. For example, drought resulting from higher temperatures might shift the role of peatland from a CO_2 sink to a source, although higher temperatures with more water availability (through precipitation or rewetting) can promote more production than respiration and maintain the carbon sink (Salimi et al. 2021; Vanselow-Algan et al. 2015). Shoreline erosion due to sea-level rise or frequent and extreme weather events (triggered by climate change) cause losses of salt marshes and mangrove forests.

Reduce the conversion of wetlands for agriculture, urbanization, aquaculture, or coastal development

As noted, wetlands have some of the highest stores of soil carbon in the biosphere, storing more than 30 per cent of the estimated global carbon emissions (Nahlik and Fennessy 2016). Hence, maintaining these existing carbon pools in wetlands is important as their loss could significantly increase the concentration of atmospheric CO_2, further contributing to the climate crisis (Anisha et al. 2020). Between 1970 and 2015, the area of the world's natural inland and coastal wetlands declined by around 35 per cent (Ramsar Convention on Wetlands 2018). About 15 per cent of the world's peatlands have been drained for agriculture, forestry, and grazing, leading to release of the carbon stored in their soils and resulting in at least 5 per cent of the total global anthropogenic emissions (Joosten et al. 2012; Tanneberger et al. 2017). Mangrove forests have also experienced a loss of around 4.3 per cent globally in the 20 years preceding 2016, due predominantly to direct human impacts (urbanization, aquaculture, and agriculture) (Global Mangrove Alliance 2021). Preventing human-induced degradation of wetlands that leads to GHG emissions is also important. A meta-analysis on GHG emissions from global wetlands due to conversion estimates that at least 0.96 ± 0.22 Gt CO_2-e of GHG is released to the atmosphere each year from natural wetlands being drained, accounting for 8.0–9.6 per cent of the annual global GHG emissions estimated by IPCC (2014). Drainage of all wetlands will result in increased emissions of CO_2 as the soil organic matter is allowed to decompose. To formulate a mitigation strategy, it is important to understand the context-specific wetland management required for emissions reduction (Anisha et al. 2020). The management of the landscape surrounding a wetland also plays an important role in reducing emissions, particularly regarding nutrient control. Vegetation structure and level of degradation, tree density, livestock grazing intensity, etc., can impact soil water content, groundwater tables, soil nutrients, soil salinity, and several other factors, and thus have a significant impact on annual GHG fluxes (Han et al. 2014; Herbst et al. 2013; Tan et al. 2020).

Restoration of wetlands to increase carbon sequestration capacity

Different types of wetlands sequester carbon and emit GHGs in various ways. When restoring wetlands, it is essential to understand the sequestration mechanisms and carbon dynamics specific to each wetland type and region to increase the capacity of wetlands to actively sequester carbon over the long term (Mazurczyk and Brooks 2018). Hydrological regime, climate, wetland soil type, sediment deposition, decomposition rate, and vegetation usually play important roles in a wetland's carbon storage mechanism (Mazurczyk and Brooks 2018; Mitsch et al. 2010; Mitsch et al. 2013; Moomaw et al. 2018; Zhang et al. 2002; Zhao et al. 2019). The sequestration rate in temperate and tropical wetlands is four to five times greater than that found in boreal wetlands (Mitsch et al. 2013). Examining more specific examples, Zhao et al. (2019) studied the effects of water level and inundation duration on CO_2 uptake in the Everglades National Park in the USA and suggested that there was lower net CO_2 uptake during extended periods of high water, while a study on the impacts of drought conditions on wet soils suggests that decomposition rates and the subsequent carbon storage in peatlands and mineral soil wetlands differ during drought periods (Stirling et al. 2020). The effects of the hydrological regime vary widely for different types of wetlands based on their region, and is one of the many drivers of carbon sequestration and GHG release in those wetlands.

In addition to water quantity and the surrounding land use, water quality plays a vital role in the emissions pattern from freshwater ecosystems. To initiate greater carbon storage, one method would be to slow the rate of decomposition, which is directly related to the biochemical and physicochemical processes (e.g., lack of available oxygen, pH, nutrients, conductivity, etc.) in the wetland (Mazurczyk and Brooks 2018; Moomaw et al. 2018; Pinsonneault et al. 2016; Weil and Brady 2016). For example, low pH reduces microbial activity, which lowers the decomposition rates. Temperature changes affect the microbial and plant activity and influence the carbon storage capacity. Decomposition rates increase exponentially with temperature, resulting in more carbon release (Batson et al. 2015a; Mazurczyk and Brooks 2018; Moomaw et al. 2018). Plant productivity and species composition are important in this regard and another proposed strategy to increase carbon storage in a wetland is to increase native species and fungi-based processes by planting perennial species.

Wetlands include many different ecosystems, such as peatlands, mangroves, marshes, swamps, and bogs. The following sections highlight ecosystems with especially high impact on climate mitigation.

Restoration and reduced conversion of peatlands

Peatlands are a kind of wetland where the organic matter from decomposing plants forms peat layers in the soil. Restoration and reduced conversion of peatlands have strong long-term mitigation potential. IPCC estimates a yearly emissions reduction potential of 0.45–1.22 and 0.15–0.81 Gt CO_2-e/year respectively for reduced peatland conversion by drainage and burning respectively (IPCC 2022). Peatlands occur in all climate zones, from boreal to tropical. Globally, peatlands cover about 3 per cent of the landmass (Gorham 1991), or approximately 4.2 million square km (Xu et al. 2018). The area of peatlands in temperate and boreal regions is around 3.7 million square km, storing a total carbon stock of 415 petagrams (GtC: 10^{15} grams of carbon) (Hugelius et al. 2020; Yu 2012). The extent of tropical peatlands is about 450,000 square km, occurring in regions of Africa, America, and Asia, storing about 105 GtC, about 20 per cent of the carbon stock in high latitudes (Dargie et al. 2017; Rieley and Page 2016). The extensive carbon sink capacity of peatlands plays an important role in the global climate system and these systems have exerted a cooling effect due to their sustained carbon sequestration over millennia despite their substantial methane emissions (Frolking et al. 2006; Kirpotin et al. 2021). It is estimated that investing in healthy and well-managed peatlands may achieve reductions of at least 5 per cent of global anthropogenic CO_2 emissions (Joosten 2016). The soils of peatlands at high latitudes generally contain >65 per cent organic matter (Kolka et al. 2016), while tropical peatland soils contain as much as 99 per cent (Anshari et al. 2010; Page et al. 2011b). The primary constituent of organic matter is elemental carbon, and the carbon stock in tropical peat might be larger than current estimates, as areas of these wetlands may be underestimated (Gumbricht et al. 2017; Murdiyarso et al. 2019).

However, like other wetlands, peatlands are being degraded worldwide, causing many peatlands to turn from carbon sinks to carbon sources. Anthropogenic disturbances such as peat harvesting, drainage, peat fires, and land use changes, are major drivers that cause peat to become a source of atmospheric CO_2 (Andersen et al. 2013; Conchedda and Tubiello 2020; Hooijer et al. 2015; Kolka, et al. 2016; Loisel and Bunsen 2020; Moore et al. 2013). The amount of GHG emissions originating from drained peat globally is about 6 per cent of the global CO_2 emissions (Joosten et al. 2012). Under present land use management regimes, Urák et al. (2017) predicted about 25 per cent of peatland areas would degrade by 2050 and contribute 8 per cent of global CO_2 emissions. Using model-based projections of future peatland dynamics, Humpenöder et al. (2020) demonstrates that conservation and restoration of about 60 per cent of currently degraded peatlands is required to return the land system to a net CO_2 sink within the 21st century. Peatland conservation and restoration therefore have a large climate mitigation potential and need to be at the heart of climate policies (Menichetti and Leifeld 2018).

For northern peatlands, prompt post-disturbance rewetting and revegetating has been shown to substantially reduce adverse climate impacts from degraded peatlands (Günther et al. 2020; Nugent et al. 2019) and to return the carbon sequestration function of peatlands within a decadal timeframe (Nugent et al. 2018). Restoring natural hydrology and water table depth in peatlands is an important factor for the successful restoration of peatland ecosystem services (e.g., Gaffney et al. 2020) and has been shown to substantially reduce GHG emissions from drained peatlands (Evans et al. 2021). However, climate warming is expected to increase northern peatland water losses to the atmosphere through enhanced evapotranspiration, putting peatland restoration success (and water security for human and economic purposes) at risk (Helbig et al. 2020). Long-term monitoring of GHG emissions from restored peatlands thus provides an important tool to quantify sustained climate benefits and to improve carbon credit schemes for peatland restoration projects (Günther et al. 2018).

For tropical peatlands, critical measures include restoration of degraded peat and development of sustainable peat management to mitigate and adapt to climate change (Humpenöder et al. 2020; Menichetti

Tropical peatland burning in south Thailand. Source: Shutterstock.

and Leifeld 2018), including rewetting. Tropical peat forests showed resilience to natural disturbances of past climate change in the mid Holocene and late Pleistocene (Cole et al. 2019; Hapsari et al. 2018; Ruwaimana et al. 2020). Sorensen (1993) estimated that rates of carbon sequestration in tropical peat swamp forests in Indonesia ranged from 0.01 to 0.03 Gt per year. Intact tropical peat forests are rich in biodiversity in both terrestrial and associated aquatic habitats, but these are not properly valued for their wider benefits (Thornton et al. 2020). When many peat forests in Indonesia were logged from 1970 to the 1990s, selected commercial timber species were removed and sold to earn foreign currency. This deforestation was then followed by conversion to agricultural land rather than allowing for peatland recovery. These anthropogenic disturbances caused long-lasting cultural and environmental damage that affected local livelihoods, reduced carbon stocks, and decreased biodiversity and ecosystem services (Anshari et al. 2022; Gandois et al. 2020; Hoyt et al. 2020).

The Ramsar Convention 2021 Global Wetland Outlook stated that "Rewetting does not reduce emissions to zero: emissions depend on the extent to which the peatland water-table can be raised and kept high", emphasizing the need for monitoring, long-term planning, and sustainable management. The report also notes that despite high methane emissions at the initial stage of rewetting, the amount decreases over time when peat accumulation restarts, and the contribution of restored peatlands to global warming is less than that when in a drained state (Ramsar Convention on Wetlands 2021).

Restoration and reduced conversion of tidal wetlands

Tidal wetlands, often called coastal wetlands, include seagrass meadows, tidal swamps (freshwater and saline mangrove swamps), and marshes (tidal wetlands without trees). Coastal wetlands may extend to the landward extent of tidal inundation and seaward to the maximum depth of vascular plants (Mitsch and Gosselink 2015; Wolanski et al. 2009). Rates of carbon accumulation are estimated to be 31.2–34.4 teragrams (TgC: 10^{12} grams of carbon) per year for mangrove swamps, 4.8–87.2 TgC/year for salt marshes, and 41.4–12 TgC/year for seagrass meadows (Howard et al. 2017; Kennedy et al. 2013). The coastal wetlands most affected by freshwater inputs are located in deltas and estuaries, where rivers and streams mix with seawater. Today, all three types of tidal wetland habitats face threats that can affect them in different ways,

Elkhorn Slough tidal marsh restoration project, U.K., which aims to restore 147 acres of vegetated tidal salt marsh, and native grasslands. Source: Shutterstock.

including activities in watersheds such as agricultural intensification, urbanization, and nutrient pollution. For example, a lack of sediment supply threatens marshes and mangrove swamps, while reduced water clarity can threaten seagrass meadows. Sustainability of tidal forests and marshes is dependent upon continued vertical accretion of soil to maintain the surface elevation with respect to sea level (Kirwan and Megonigal 2013), which is expected to rise at increasing rates with global warming (IPCC 2021). Increased sediment supply enhances this process while increased nitrogen from watersheds can cause a decline in production of the roots that are key to soil accumulation and the storage of carbon below ground (Darby and Turner 2008; Deegan et al. 2012). Delivery of excess nitrogen affects the ability of the tidal wetland to mitigate climate warming as microbial activity can transform some of it to nitrous oxide, a greenhouse gas with 265 times the global warming potential of CO_2 (on a 100-year timescale) (Myhre et al. 2013; Roughan et al. 2018). Nutrients are supplied to coastal waters from watersheds where sources are agriculture, sewage, and run-off from urban land.

Upstream dams reduce the level of suspended sediment released from watersheds; even ‘mini-dams’ for hydropower, which are purported to have less environmental impact, can reduce sediment loads. With respect to coastal wetlands, mini-dams have little advantage as they still retain sediments and in multiple numbers would have a considerable cumulative impact akin to the situation of the small dams built to power mills in the northeastern USA. Even as old dams are being removed (e.g., in USA), new ones are being constructed and continue to be planned in other regions such as Mexico. Many environmental and social factors are addressed when assessing the impact of dams, but generally these assessments have not included impacts on tidal wetlands. Promoting awareness of the links between sediment retention and loss of tidal wetland carbon sinks, along with the potential for obtaining carbon credits as an alternative income source, may encourage more balanced judgements when selecting sites for new dams.

Restoration and reduced conversion of inland mineral-soil (IMS) wetlands

IMS wetlands (or freshwater mineral-soil wetlands) include freshwater marshes and freshwater swamps. IMS wetlands account for approximately 39 per cent of the total wetland area globally (Badiou 2017). These freshwater wetlands have significant carbon stocks due to their high productivity and waterlogged condition (Bernal and Mitsch 2012; Mitra et al. 2005). Carbon sequestration in IMS wetlands occurs when in situ biomass production exceeds decomposition rates (Bridgham et al. 2006; Mazurczyk and Brooks 2018; Moomaw et al. 2018). Like peatlands, IMS wetlands play an important role in climate change mitigation. The rate of carbon sequestration in peatlands is low compared with that of IMS wetlands (Bernal and Mitsch 2012; IPCC 2014; Zhang et al. 2016). A study on the IMS wetlands in the Great Plains, USA suggests that most of these organic soil carbon stocks were held in herbaceous freshwater mineral soil wetlands and the rest was found in woody freshwater mineral soil wetlands (Byrd et al. 2015). Carbon stocks in IMS wetlands vary from 12 to 557 tons per hectare, depending on the type of wetland and climate (Ausseil et al. 2015; Bernal and Mitsch 2008; Page and Dalal 2011). CO_2 and methane fluxes from IMS wetlands vary depending on the hydrology, soil wetness, land use type (e.g., disturbed or restored), sediment texture, and vegetation (Batson et al. 2015b; Hondula et al. 2021; Pfeifer-Meister et al. 2018).

Research on seasonally inundated forested IMS wetlands reveals that inundated soils switch from methane sources to sinks depending on water level, soil moisture, and the direction of water-level change (rising or falling). In fact, it is reported that methane emissions are associated with inundation extent and duration, but not frequency or depth, and that emissions are increasing with droughts and decreasing water levels (Hondula et al. 2021). An increase in CO_2 emissions is also observed with soil drainage and emissions are reduced by 49 per cent under long-term waterlogging (Tete et al. 2015). Significant nitrous oxide emissions are also associated with frequent drying of wetlands (Badiou, 2017; Pennock et al. 2010). Frequent wetting and drying events in IMS wetlands result in increased methane emissions compared with static water-level conditions (Badiou 2017; Hondula et al. 2021; Malone et al. 2013; Tete et al. 2015).

It is common practice to drain IMS wetlands as part of the preparation of land for agriculture, grazing, and forestry. A lower water level due to drainage leads to higher rates of decomposition, resulting in reduced carbon stocks (Page and Dalal 2011). Land conversion results in loss of stored carbon in soil through mineralization, which was otherwise protected against due to the anaerobic conditions (Mitra et al. 2003).

Many other anthropogenic activities such as levee, dam, and dike construction; irrigation; flow manipulation for water supply; and wildlife management can significantly alter the hydrology of IMS wetlands within the landscape (IPCC 2014; Mitsch and Gosselink 2015). Several studies demonstrate an increase in methane and nitrous oxide emissions due to increased nutrient loading from anthropogenic activities and land use (Gonzalez-Valencia et al. 2014; Silva et al. 2016).

The soil carbon accumulation and sequestration rates are much higher in natural unaltered IMS wetlands compared with restored wetlands, but over the long term, restored IMS wetlands have potential to regain a carbon stock similar to that of natural wetlands depending on factors such as hydrology, vegetation, soils, and land use (Bruland and Richardson 2005; Tangen and Bansal 2020). Many studies suggest that CO_2 contributes the most to the total GHG emission profile from restored IMS wetlands, while methane and nitrous oxide contribute much less. Soil saturation has been identified as a key limiting factor in methane and nitrous oxide production in restored wetlands (Gleason et al. 2009; Nahlik and Mitsch 2010; Phillips and Beeri, 2008; Richards and Craft 2015). Studies suggest that restored and recreated IMS wetlands have higher carbon sequestration rates and shorter time periods in making the transition from a net source to a net sink than many other restored or created ecosystems (Badiou 2017; Euliss Jr et al. 2006).

Wetland mitigation measures relevant in future planning and implementation

The following wetland mitigation measures can be considered in future climate mitigation planning and implementation.

- **Conserve existing wetlands:** It is crucial to conserve existing wetlands with their carbon pools and prevent further degradation, as their loss could significantly increase the concentration of atmospheric CO_2.

- **Restore wetlands:** Wetland restoration has a large climate mitigation potential and needs to be at the heart of climate policies. For example, for northern peatlands, it is important to initiate the rewetting and revegetating as soon after the disturbance as possible to substantially reduce adverse climate impacts and to return the carbon sequestration function. Restoring natural hydrology and water table depth in peatlands is an important factor for the successful restoration of peatland ecosystem services.

- **Context-specific management:** It is important to understand context-specific wetland management for emissions reduction when developing strategies and measures. The management of the landscape surrounding a wetland plays an important role in reducing emissions, particularly regarding nutrient control. Vegetation structure and level of degradation, tree density, and livestock grazing intensity, etc., can impact soil water content, groundwater tables, soil nutrients, soil salinity, and several other factors, and thus have a significant impact on annual GHG fluxes.

- **Measures for increased carbon storage:** It is possible to increase the carbon storage capacity of wetlands by implementing measures suited to specific wetlands. For example, water quality plays an essential role in the emissions pattern from wetlands. To initiate greater carbon storage, one method would be to slow the rate of decomposition, which is directly related to the biochemical and physicochemical processes. Also, plant productivity and species composition are important and another proposed strategy to increase carbon storage in a wetland is to increase native species and fungi-based processes by planting perennial species.

- **Understand specific wetland types:** Different types of wetlands sequester carbon and emit GHG in various ways. It is crucial to understand the sequestration mechanisms and carbon dynamics specific to each wetland type and region to increase the capacity of wetlands to actively sequester carbon over the long term.

- **Promote wetland awareness for selecting dam sites:** Upstream dams reduce the level of suspended sediment released from watersheds, which impacts tidal wetlands. Promoting awareness of the links between sediment retention and loss of tidal wetland carbon sinks along with the potential for obtaining carbon credits as an alternative income source may encourage more balanced judgements when selecting sites for new dams.

- **Monitoring of GHG emissions:** To make informed decisions regarding peatland restoration, long-term monitoring of GHG emissions from restored peatlands provides an important tool to quantify sustained climate benefits and to improve carbon credit schemes for peatland restoration projects.

Knowledge and data gaps in the mitigation potential of wetlands

The following knowledge and data gaps should be filled to maximize the mitigation potential of wetlands.

- Many countries in the world either do not have a national wetland inventory or are still in an initial stage of developing one. For instance, there is substantial uncertainty regarding the spatial extent of tropical peatlands and associated carbon stocks. More field data is needed to reduce these uncertainties and protect these ecosystems.

- Conservation and restoration of wetlands can have socio-economic trade-offs (see section 5.3). There needs to be a framework that can be used to assess potential trade-off scenarios.

- There is limited knowledge on how to restore degraded peatlands. More research, monitoring, and evaluation of existing restoration interventions is needed to make informed decisions, for instance regarding the hydrological system, drainage conditions, types of peat soils, climate, land use, and long-term climate change impacts.

- Research and efforts should build on emerging findings on the impact of thawing permafrost regions and develop guidance on mitigating large-scale carbon and methane release.

5.2.2 Mitigation measures in rivers and streams

River systems can store a significant portion of terrestrial carbon, but due to lack of research and data the estimated mitigation potential is not known. Still, inland waters are increasingly recognized as a significant source of GHG emissions (Zhang et al. 2021), while riverine floodplains have been acknowledged for their carbon storage (Sutfin et al. 2016). Rivers and streams do not just connect the carbon stocks of land and sea (Ran et al. 2015), but are also biogeochemical integrators in landscapes, both receiving and processing carbon, nitrogen, and phosphorus, and other biologically active elements (Crawford et al. 2017).

Enhanced carbon storage in river systems

River systems are often referred to as river corridors, which include the active channel and the riparian zone (floodplain and hyporheic zone beneath the stream or river) (Harvey and Gooseff 2015). In a river corridor, organic carbon is stored in six forms, among which three primary reservoirs are: i) fallen dead large wood in the channel and floodplain; ii) standing biomass of riparian vegetation; and iii) soil organic carbon (SOC), which is technically the organic carbon on and beneath the floodplain surface. Fallen large wood, with its long residence time in a river and floodplain, stores organic carbon and delivers particulate organic matter (POM) to the channel and the floodplain. Vegetation is also a significant reservoir of organic carbon. However, floodplains are critical since they do not just support the biomass growth that is a source of large wood, they facilitate the transport, accumulation, retention, and breakdown of organic matter received from the channel and the riparian vegetation (Sutfin et al. 2016; Robertson et al. 1999; Wohl et al. 2017). A recent evaluation of carbon sinks within Amazonian floodplain lakes estimates that the accumulation of carbon may exceed the rate of emission from the river system (Sanders et al. 2017).

Several factors determine the carbon storage potential of a river corridor, including geology, climate, channel complexity, valley geometry, hydraulic connectivity, microbial activity, and riparian vegetation. As a river moves through different landscapes, the above-mentioned factors influence the travel time and retention of water, sediment, and organic carbon. For example, a high degree of channel complexity increases the residence time of water, sediment, and POM; facilitates the breakdown of organic matter; and filters excess nutrients and dissolved organic carbon (DOC) from surface and shallow subsurface waters (Sutfin and Wohl 2017; Sutfin et al. 2016; Wohl et al. 2017).

The surface and shallow subsurface of the floodplain host a large reservoir of organic carbon as SOC. For both small and large rivers, carbon is stored predominantly in the floodplain soil. During overbank

Unchallenged spring overflow of the Pripyat River, Ukraine. Source: Shutterstock.

flooding, floodplains also act as sinks for inorganic, organic, dissolved, and particulate fractions of both nitrogen and phosphorus (Noe and Hupp 2005; Wohl et al. 2017). Long-term carbon storage in the floodplain is determined by the source and form of organic carbon as well as the residence time of the floodplain sediment. A longer residence time enables the retention of sediments and organic carbon. Once stored in the floodplain soil, even DOC and POM take many years to travel through the river network (Cierjacks et al. 2010; Sutfin et al. 2016). This function of floodplains has been observed in different ecoregions, such as mountainous floodplains and tropical semi-arid lowland floodplains (Omengo et al. 2016; Scott and Wohl 2018; Sutfin and Wohl 2017).

In addition, hydrologic connectivity impacts the carbon sequestration potential of floodplains. Hydrologic connectivity exists longitudinally within channels, laterally between floodplains and channels, and vertically between surface water, hyporheic flow, and groundwater. While lateral and longitudinal hydrologic connectivity facilitate the transport, accumulation, retention, and breakdown of organic matter, lateral and vertical connectivity, on the other hand, facilitate saturated conditions in floodplains which limit decomposition of organic matter, microbial metabolism, and mineralization of SOC. Transport of organic matter from catchments occurs longitudinally and then laterally between floodplains and river channels. Increased carbon accumulation and storage is facilitated by increased lateral and vertical hydrologic connectivity. When the lateral connectivity between stream and floodplain is interrupted, there is decreased retention of water and sediment, which results in reduced carbon sequestration (Sutfin et al. 2016).

Several anthropogenic activities affect the carbon storage capacity of floodplains, particularly the disconnection of floodplains from the active channel through various activities. Some common examples are constructing levees and embankments, bank stabilization, conversion of floodplains to agricultural land, and urban expansion (Noe and Hupp 2005; Robertson et al. 1999; Shen et al. 2021). Construction of levees and embankments confine the active channel and alienate the floodplain, limiting overbank flows and lowering the rate of carbon deposition and sequestration (Wohl et al. 2017). Flow regime changes through damming, dredging, straightening, and/or bank stabilization can alter the quality of in-channel organic matter and increase downstream fluxes (Robertson et al. 1999; Sutfin et al. 2016).

GHG emissions from rivers

Recent studies on GHG emissions from inland waters reveal emission rates that are higher than previously estimated (Raymond et al. 2013; Saunois et al. 2020; Tian et al. 2020). The methane emissions from inland water systems are now estimated to range from 117 to 212 Tg per year, nearly an order of magnitude greater than the initial estimate of 1.5 Tg per year (DelSontro et al. 2018; Saunois et al. 2020). In the case of nitrous oxide, rivers and streams can be considered as a significant source, depending on the organic matter and nutrient availability and other water quality parameters such as temperature, dissolved oxygen, and pH (Quick et al. 2019; Stanley et al. 2016; Zhang et al. 2021). Although nitrous oxide emissions from rivers had started to decline between 2010 and 2016 (due to decreased use of nitrogen fertilizers), a four-fold increase was seen in 2016 compared with 1900, i.e., 291.3 ± 58.6 gigagrams of nitrous oxide nitrogen per year (Gg N_2O-N/year) versus 70.4 ± 15.4 Gg N_2O-N/year (Maavara et al. 2019; Seitzinger et al. 2000; Yao et al. 2020).

Although there is evidence that rivers are emitting GHGs, there is no comprehensive knowledge about the drivers of emissions, their pattern, or their variability. The understanding of emissions from rivers is still constrained by a relatively small number of observations scattered around the world. These observations vary in measurement and upscaling methods, and have significant spatial and temporal fluxes and uncertainties (Allen and Pavelsky 2018; Crawford et al. 2017; Maavara et al. 2019; Natchimuthu et al. 2017; Zhang et al. 2021). Table 5.2 below synthesizes these findings.

Table 5.2. Synthesis of studies on riverine emissions

STUDY SITE	GHG	KEY FINDINGS	SOURCE	STUDY APPROACH
Chaohu Lake basin, China	N2O CH4 CO2	Urban rivers are emission hotspots (compared with forested and agricultural rivers). Large nutrient supply and low oxygen levels drive the relatively high emissions from urban rivers.	Zhang et al. 2021	This study investigates spatial variability of N2O, CH4, and CO2 emissions from river reaches that drain from different types of landscapes (i.e., urban, agricultural, mixed, and forest landscapes).
Sweden	N2O	Agricultural and forest streams have comparable N2O fluxes despite higher TN concentrations in agricultural streams. The percentage saturation of N2O in the streams is positively correlated with stream concentration of TN and negatively correlated with pH. The different TN concentrations but similar N2O concentrations in both types of streams have been attributed to the low pH (<6) of forest soils and streams.	Audet et al. 2020	This study analysed a data set comprising approximately 1,000 stream N2O concentration measurements from agricultural and forest streams in Sweden covering temperate to boreal zones, especially low-order streams.
USA	CO2	Streams and rivers in the USA are supersaturated with carbon dioxide when compared with the atmosphere, emitting 97±32 Tg carbon each year. The correlation between precipitation and CO2 evasion is stronger than that of discharge and evasion due to the expansion of the river surface area with greater delivery of water through precipitation and higher flushing and delivery of soil and riparian/wetland CO2.	Butman and Raymond 2011	The study included total conterminous US streams/rivers with a surface area of 40,600 km2.
Meuse River, Belgium	N2O CH4 CO2	Surface waters are oversaturated in CO2, CH4, N2O, acting as source of GHG to the atmosphere. Highest GHG fluxes were observed during low water. Highest GHG fluxes were observed in agriculture-dominated catchments.	Borges et al. 2018	The study includes four seasonal surveys covering 50 stations, from yearly cycles in four rivers of variable size and catchment land cover, and from 111 groundwater samples.

STUDY SITE	GHG	KEY FINDINGS	SOURCE	STUDY APPROACH
Tibetan Plateau	N_2O CH_4 CO_2	The correlation between the precipitation and CO_2 emissions is stronger than that with DOC concentrations and water temperature (due to greater flushing and delivery of soil and riparian/wetland CO_2 to streams and rivers). A positive trend in CH_4 concentrations with the increased DOC concentrations was observed, indicating that water temperature placed a certain influence on driving pressure of CH_4 increased in anaerobic decomposition . Partial pressures of N_2O were correlated with dissolved nitrogen and were higher in main streams of the Tibetan rivers than those in tributaries due to anthropogenic activities around the mainstream.	Qu et al. 2017	The study undertook one-time sampling from 32 sites in rivers of the Tibetan Plateau during2014 and 2015.
Sub-Saharan Africa	N_2O CH_4 CO_2	Riverine carbon dioxide and methane emissions increase with wetland extent and upland biomass. A positive relationship was found between CO_2 and CH_4 flux and precipitation across the region, with the exception of two Malagasy rivers.	Borges et al. 2015	The study is based on 12 rivers in sub-Saharan Africa, including seasonally resolved sampling at 39 sites, acquired between 2006 and 2014.
Amazonian Basin	CH_4	Biological oxidation in large Amazonian rivers is a significant sink of CH_4, representing up to 7 per cent of the global soil sink. The capacity for MOX can vary widely across various river types and hydrologic regimes. The future river MOX process might be sensitive to environmental change, adding to the list of important climate feedback on natural GHG emissions.	Sawakuchi et al. 2016	The study examines the cycling and flux of CH_4 in six large rivers in the Amazon basin, including the Amazon River in the year 2012, during high water and low water seasons. MOX rate has been studied. MOX reduces the diffusive flux of CH_4 in the rivers.
Amazon and Congo	CH_4 and CO_2	The pressure of CO_2 and CH_4 concentrations significantly increased from the main stream to the small tributaries in both the rivers. The analysis indicated a stronger contribution of CO_2 production from anaerobic organic matter degradation compared with aerobic respiration, which is speculated to be related to carbon processing within the wetlands in the vicinity.	Borges et al. 2015	This study compares the CO_2 and CH_4 distributions in lowland river channels of the two largest rivers in the world and in the tropics, the Amazon (n=136) and the Congo (n=280), using a dataset of concurrent CO_2 and CH_4 concentration measurements in river channels

Note: N_2O = nitrous oxide; CH_4 = methane; CO_2 = carbon dioxide; TN = total nitrogen; DOC = dissolved organic carbon; MOX = methane oxidation

Despite a lack of coherent and generalized knowledge available to explain emissions from rivers, and how to minimize these, some observations are common across several studies. Nutrient loading and organic matter delivery due either to anthropogenic activities (urbanization or agriculture) or to natural causes (vegetation or wetlands) are observed to increase river saturation with CO_2, methane, and nitrous oxide. However, a combined impact of multiple factors such as geomorphologic and hydrologic conditions, temperature, alternative electron acceptors, pH, etc. can influence the emission of GHGs. For example, Stanley et al. (2016) illustrates how the concerted impact of several factors influences methane emissions in rivers (Figure 5.1). Some studies found a strong correlation between precipitation and CO_2 emissions due to greater flushing and delivery of soil and riparian/wetland carbon to streams and rivers (Borges et al. 2015; Qu et al. 2017; Butman and Raymond 2011). Borges et al. (2015) attempted to draw parallels between two major rivers in the tropics and concluded that "dynamics of dissolved CH_4 [methane] in river channels are less straightforward to predict and are related to the way hydrology modulates the connectivity between wetlands and river channels." In fact, the main streams and tributaries of the same river tend to emit differently, and the emission rates tend to change based on the stream orders (Audet et al. 2020; Borges et al. 2015; Qu et al. 2017; Raymond et al. 2013; Zhang et al. 2021).

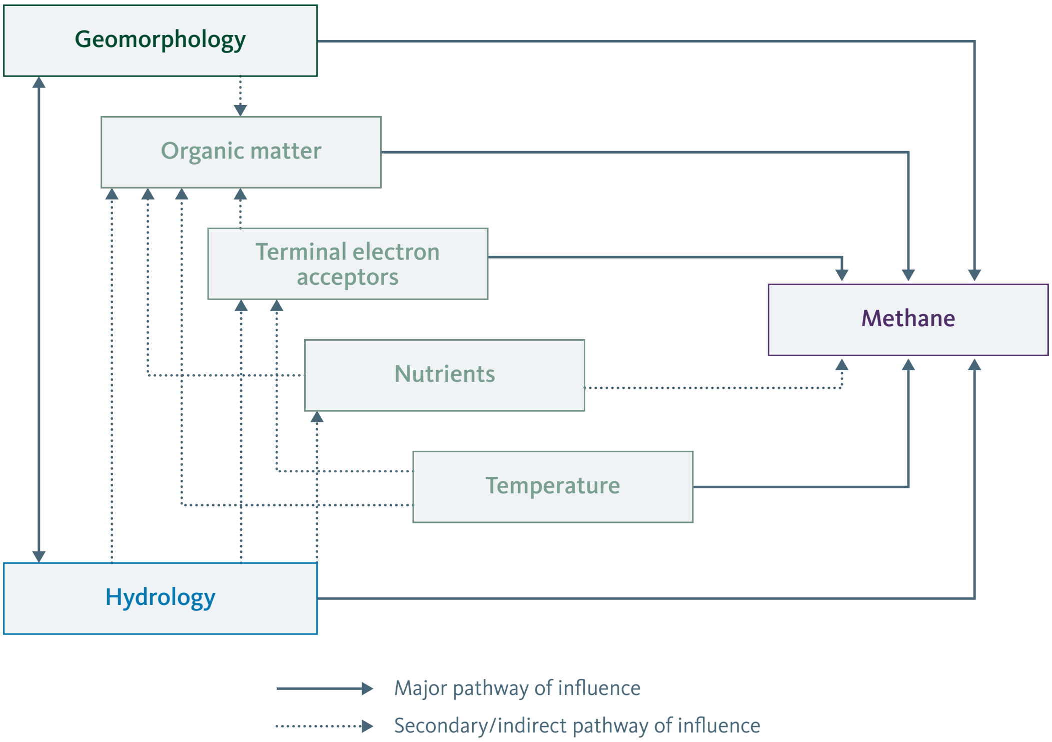

Figure 5.1. Conceptual framework of controls on methane production and persistence in rivers. Controls mentioned here are geomorphology, hydrology, organic matter, temperature, terminal electron acceptors, and nutrients. Source: adapted from Stanley et al. (2016).

River mitigation measures relevant in future planning and implementation

The following river system mitigation measures, many of which align with general principles for managing the health of rivers, can be relevant to consider in future climate mitigation planning and implementation.

- **Connecting rivers with floodplains**: Construction of levees and embankments confines the active channel and alienates the floodplain as well as limiting overbank flows, which lowers the rate of carbon deposition and sequestration in floodplains. Maintaining lateral connectivity and ecosystem integrity in riparian areas can help increase the carbon pool in the floodplains. Floodplains work as buffers and reduce nutrient loading to the channels, which can help reduce emissions.
- **Limiting channel alterations**: It is important to protect and restore the physical complexity and flow regime of river corridors, which enable carbon storage. Channel alterations through dredging, straightening and/or bank stabilization can alter the quality of in-channel organic matter and increase downstream fluxes. Maintaining the lateral and vertical hydrologic connectivity of rivers enhances carbon sequestration potential to a greater extent than enhancing longitudinal connectivity.
- **Limiting nutrient and organic matter loading in rivers**: Nutrient loading and organic matter delivery, either due to anthropogenic activities (urbanization or agriculture) or due to natural causes (vegetation or wetlands), are observed to saturate rivers with CO_2, methane, and nitrous oxide. Monitoring, managing, and limiting nutrient and organic matter loading in rivers can

reduce GHG emissions from rivers. Connecting rivers with floodplains also reduces nutrient loading in channels, which can help reduce emissions.

- **Context-specific monitoring**: The carbon sequestration potential of river corridors depends on regional and local controls, such as geology, climate, hydrology, geomorphic characteristics, etc. Also, for emissions, the main channel and tributaries of the same river tend to emit differently, and the emission rates tend to change based on the stream orders. Studies also suggest that the variation in emissions in different river reaches is related to their proximity to urban, agricultural, or forested landscapes. It is unlikely that there will be a generalized solution that fits all rivers, and management plans should be context specific.

- **Undertake watershed-scale management approaches**: Whether for enhanced carbon sequestration or emissions reduction, management approaches and decisions should be taken at the watershed scale. Carbon fluxes in rivers are affected by grazing, cropping on floodplains (nutrient source), or soil erosion due to removal of native species (POC loading). Rather than treating river systems as isolated segments, watershed-scale management that addresses the complex dynamics of the catchment can yield better outcomes.

Knowledge gaps in the mitigation potential of rivers and streams

Significant knowledge gaps remain, particularly the following, and it is critical to address these to realise the full mitigation potential of rivers and streams.

- Understanding of the spatial extent and magnitude of changes in riparian soil organic carbon content and biomass is currently based on only a handful of studies focused on limited regions. There is no global-scale comprehensive understanding of how historical and ongoing riparian modification impacts carbon dynamics in river systems.

- Carbon flux mechanisms and their transformations in the river corridors, as well as the impacts of future climate change on river corridors, must be better understood.

- Knowledge and understanding of the complex and nonlinear interactions among water, sediment yield, flow regime, biomass and primary productivity, soil moisture, and/or soil organic carbon must be developed.

- There is a need for more holistic studies to estimate the emissions potential of rivers by mapping emissions of all three major GHGs.

- In several river basins, the source of pollution (e.g., from industry) and the point of sequestration (e.g., the river corridor) may not be under the same jurisdiction. Policies need to consider such gaps and find a way to minimize them.

5.2.3 Mitigation measures in lakes and reservoirs

Lakes, either natural or reservoirs created behind dams, play a key role in global carbon cycling despite taking up less than 4 per cent of the earth's non-glaciated land area (Bastviken et al. 2011; Beaulieu et al. 2020; DelSontro et al. 2018; Raymond et al. 2013; Stanley et al. 2016; Verpoorter et al. 2014). Lakes and reservoirs can trap land-derived carbon (through carbon burial) in their sediments (Mendonça et al. 2017). Mendonça et al. (2017) recommended considering lakes and reservoirs as a 'new sink' for land-derived organic carbon, particularly because organic carbon is preserved more efficiently in inland water sediments than in other depositional environments (such as soils), and sediment delivery to the sea has decreased. Cole et al. (2007) also acknowledged the high carbon burial potential of reservoirs due to high sedimentation, but also warned about the unknown fate of reservoir sediment after dam removal.

However, lakes and reservoirs also produce high levels of methane (compared with CO_2) in nutrient-rich (eutrophic) sediments (Beaulieu et al. 2020; Berberich et al. 2020; DelSontro et al. 2018). Despite considerable rates of carbon burial, eutrophic freshwater with carbon-carrying sediments can become a greater net GHG source at a centennial time scale. This is a key concern, considering the global warming potential of methane is 28 times greater than that of CO_2 over a 100-year time horizon (Myhre et al. 2013). In fact, a study by DelSontro et al. (2018) showed GHG emissions from

Algal bloom in a Bavarian lake. Source: Shutterstock.

lakes and reservoirs are equivalent to 20 per cent of CO_2 emissions from global fossil fuels every year.

Lake size, depth, sedimentation rates, DOC concentration, and productivity rate (the lake's ability to support plant and animal life defines its level of productivity, or trophic state), alongside environmental factors such as temperature and precipitation, have been identified as the drivers of GHG emissions in reservoirs and lakes (Beaulieu et al. 2019; Berberich et al. 2020; DelSontro et al. 2018; Sanches et al. 2019; Waldo et al. 2021). Shallow and tropical lakes and reservoirs have high emission rates for GHGs, but methane is of most importance due to its link with lake and reservoir productivity and its high global warming potential (DelSontro et al. 2018; Gunkel 2009; Sanches et al. 2019). A higher ratio for the watershed area compared to the surface area of the reservoir usually results in high sediment and nutrient loading from the surrounding catchment compared to that for natural lakes, triggering greater production and carbon burial, and increasing methane generation in the system (Berberich et al. 2020). Nitrous oxide emission rates are also substantially lower for natural lakes than for reservoirs when measured per mean surface area (Lauerwald et al. 2019).

An important concern with lakes and reservoirs is the high aquatic productivity in response to nutrient increase, known as eutrophication. There is a significant relationship between freshwater eutrophication and GHG emissions (Berberich et al. 2020; DelSontro et al. 2018; Li et al. 2021; Mendonça et al. 2017; Sanches et al. 2019). In fact, there is a positive feedback loop between eutrophication in lakes and reservoirs and GHG emissions, meaning that freshwater eutrophication and GHG emissions are strengthened by each other. In simple words, when nutrient loading crosses a critical threshold, submerged plants are gradually replaced by other aquatic macrophytes or algae. Firstly, a shift in the dominant primary producer (from submerged plants to algae) affects GHG emissions since submerged plants reduce methane emissions more effectively. Secondly, algae become the dominant producer in the lake or reservoir system, and this plays an important role in the freshwater ecosystem emission dynamics. Algae have a higher CO_2 uptake rate (compared with other aquatic macrophytes) and can effectively reduce CO_2 emissions. On the other hand, harmful algal blooms cause a high production of methane and nitrous oxide. Warmer temperatures increase algal production, with a corresponding increase in emissions of methane and nitrous oxide (Burlacot et al. 2020; Plouviez et al. 2019; Su et al. 2019). These increased emissions contribute further to climate change and increased temperatures (Li et al. 2021). Li et al. (2021) illustrated the positive feedback loops between freshwater eutrophication and GHG emissions (Figure 5.2). The productivity of inland waters is projected to increase in the coming decades due to both increased mean temperature and increased nutrient loading, which makes the climatic impact of harmful algal blooms an important concern (Beaulieu et al. 2019). Watershed-scale soil erosion control and nutrient reductions may help reduce GHG emissions from lakes and reservoirs (Berberich et al. 2020).

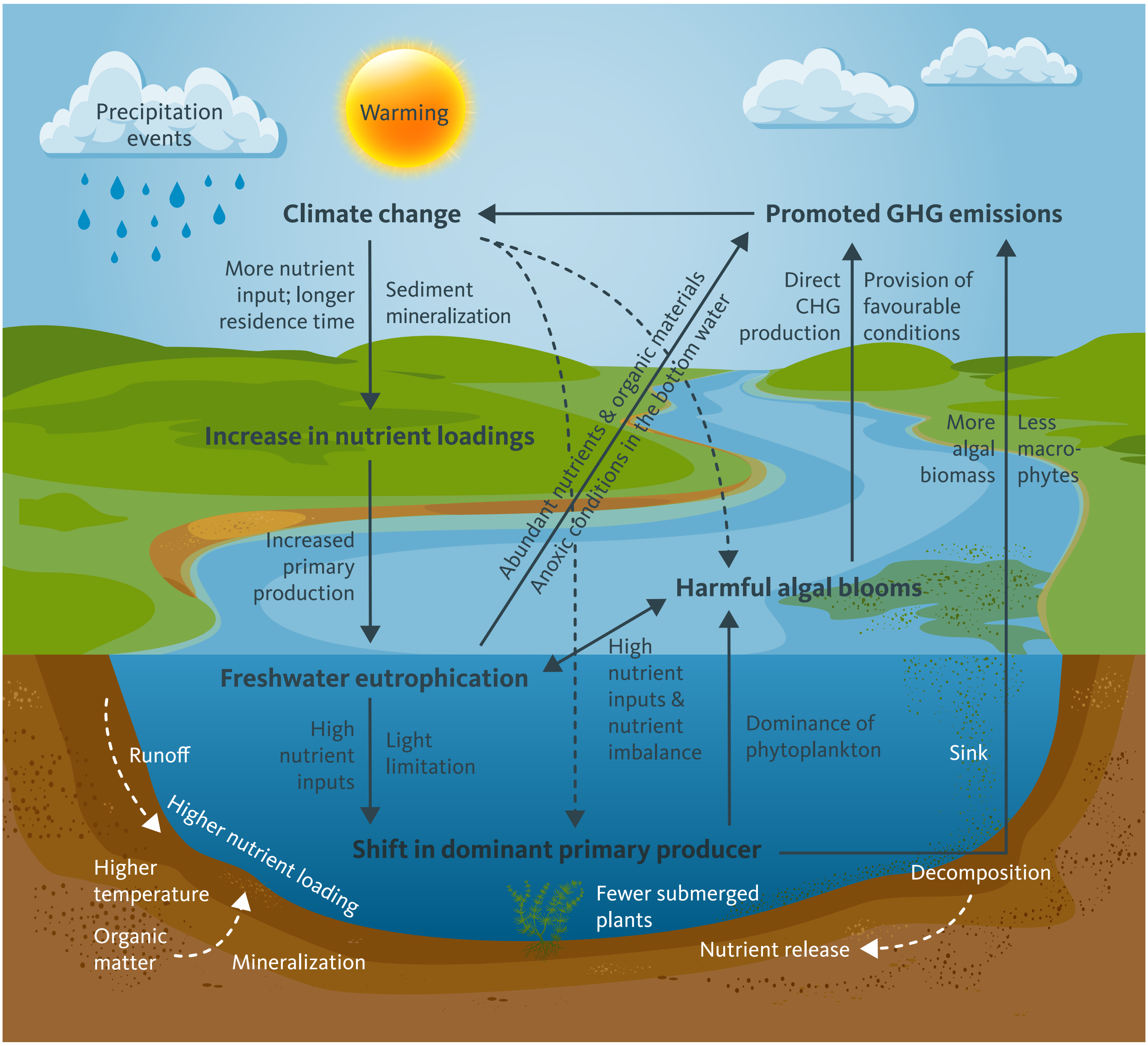

Figure 5.2. The positive feedback loops between freshwater eutrophication and GHG emissions. Source: SIWI, adopted from Li et al. 2021

High nutrient and organic matter loading are common factors influencing emissions from lakes and reservoirs, resulting in increased aquatic productivity. Lake and reservoir characteristics (depth, temperature, sediments, and rooted aquatic macrophytes) and catchment attributes (land use, terrestrial net primary production, and human activities) are also driving factors. Although reservoirs are increasingly recognized to emit significant amounts of GHGs, there are millions of small and large-scale dams, and more are being constructed all the time. It is important to discuss and implement the measures that can reduce emissions in existing reservoirs and how to reduce emissions in new reservoirs.

Lake and reservoir mitigation measures relevant to future planning and implementation

The following mitigation measures in lakes and reservoirs can be considered in future climate mitigation planning and implementation.

- **Nutrient and organic matter control for eutrophication management**: As noted, reducing nutrients, primarily nitrogen and phosphorus, and organic matter loading can lower the rate of eutrophication. This can be done by reducing use of fertilizer, minimizing nutrient loads in the catchment, phosphate stripping at sewage treatment works, and installing vegetated buffer strips adjacent to water bodies that trap eroding soil particles (Berberich et al. 2020; McCrackin et al. 2017; Paerl et al. 2020). These measures bring the added benefit of improved water quality (Li et al. 2021; Yan et al. 2021). Nutrient loading control can be a longstanding measure for ecological restoration and emissions reduction.

- **Managing drawdown, operating levels, and downstream emissions in reservoirs**: Fluctuating water tables and shallow littoral areas between dry land and open water result in considerably more methane being produced by reservoirs than by natural lakes or other surface waters (Harrison et al. 2017). Water-level management should aim to minimize methane emissions from the sediments and the littoral zone. Downstream methane emissions from reservoirs can be reduced by selectively withdrawing water from near the reservoir surface, where methane concentration is less than at greater depths (Harrison et al. 2017; Harrison et al. 2021; Keller et al. 2021; Yan et al. 2021).

- **Technology for methane management:** Methane emissions can be reduced using a methane capture technology (which converts the captured methane into energy) and a technology to increase the dissolved oxygen (such as installing an aerating device) in the water (Fearnside 2007).

- **Management of older dams and dam removal processes**: Dam removal mobilizes sediments, nutrients, and organic carbon from the reservoir resulting in a high potential for emissions. Dam removal can also affect the downstream river channel by eroding the stream bed and the nutrient-rich sediments. On the other hand, deposited nutrients do not necessarily remain trapped in the reservoir when an old or out-of-operation dam is left in place. Due to decreased sediment and nutrient elimination efficiencies, the reservoir can become a nutrient source for the surrounding landscape (Maavara et al. 2019). Hence, management of old dams and dam removal needs to consider remobilization, mineralization, and subsequent emissions of deposited sediment, nutrients, and organic carbon.

- **Conception and planning of new hydropower dams**: The role of hydropower as a clean energy source is being revisited since dams affect river ecosystems, biodiversity, and society, with a potential impact on emissions from river systems (Box 5.1). As mentioned above, emissions can occur both during years of operation and when dams are old or removed, and this should be taken into consideration. During the decision-making process for new or rehabilitated dam development, there should be thorough accounting of the short- and long-term impacts and benefits of proposed projects at the conception and planning stage, so emissions can be minimized if the development proceeds (Fearnside 2007). It is necessary to consider the GHG exchanges before and after the impoundment. The difference between pre- and post-reservoir emissions from the whole river basin indicates the GHG status of the reservoir (UNESCO/IHP 2008).

Knowledge gaps in the mitigation potential of lakes and reservoirs

Uncertainty and knowledge gaps regarding different aspects of GHG fluxes from lakes and reservoirs persist. Some of the key knowledge gaps and opportunities include the following.

- Although reservoirs emit all three major GHGs, few reservoirs have measurement records for all three, with the least number of data points for nitrous oxide (Deemer et al. 2016).

- There is noticeable variation in the estimation of GHG emissions from lakes and reservoirs. The global aerial coverage of reservoirs, including small reservoirs, is not well documented, which is why different studies used different areas and calculation periods, introducing variation in the estimation of GHG fluxes. In addition, GHG emissions from lakes and reservoirs show high spatial and temporal variability (Ion and Ene 2021; Yan et al. 2021).

- There is no standardized or widely accepted method for GHG emissions estimation in reservoirs. Until recently, emissions through ebullition and degassing pathways were not incorporated into the total GHG budget estimation. Downstream GHG emissions remain poorly studied although these could represent an important pathway of GHG release to the atmosphere (Keller et al. 2021; Yan et al. 2021).

- There is substantial uncertainty about how the impacts from climate change might affect GHG emissions from lakes and reservoirs in the future. GHG fluxes are likely to be impacted by potential changes in thae reservoirs (e.g., direct inputs, water management) and their watersheds (e.g., land use, microclimate) due to climate change (Yan et al. 2021).
- Only a handful of studies have examined the combined effects of land management change and climate change on nutrient loading, and these have been focused on individual watersheds. Socio-economic changes have an important bearing on how landscape management would be altered in the future. This uncertainty makes estimation of future GHG fluxes difficult (Sinha et al. 2019).

Box 5.1. Hydropower dams: Friend or foe?

Hydropower dams have come under increasing scrutiny over the last decade regarding their function as a clean energy source. This is because the reservoirs created by these dams emit globally significant amounts of GHGs (Deemer et al. 2016; Fearnside 2006; Fearnside 2007; Prairie et al. 2021; Tremblay et al. 2005). The total annual GHG emissions from global reservoirs amounts to 2.3 per cent of total emissions from inland freshwaters (Yan et al. 2021). Until very recently, global estimates of GHG emissions from reservoirs were based on the assumption that reservoirs located in similar climates and regions would emit in a similar manner (Harrison et al. 2021; Prairie et al. 2021). Estimation of GHG fluxes in reservoirs has also been focused solely on diffusive gas fluxes until very recently, when ebullition fluxes have also been considered in the estimation (Deemer et al. 2016; DelSontro et al. 2018; Harrison et al. 2021).

Reservoirs emit all three major GHGs, but estimation of global nitrous oxide emissions have been limited due to a scarcity of data (Deemer et al. 2016; Yan et al. 2021). CO_2 and methane are emitted in four ways: by CO_2 diffusion, methane diffusion, ebullition, and degassing. Methane emission through degassing has been incorporated in the global GHG budget of reservoirs only recently. Recent findings suggest that methane that leaves the reservoir through ebullition is transported downstream from reservoirs (Harrison et al. 2021; Keller et al. 2021). Organic content and nutrient loading, reservoir sediments, primary productivity, and water temperature are the primary contributors to GHG emissions from reservoirs, but emissions can also be affected by the characteristics of reservoirs (temperature, depth, thermal stratification, trophic status, etc.) and their catchments (land use, terrestrial net primary production, and human activities) (Yan et al. 2021; Prairie et al. 2021). Reservoir drawdown areas are hotspots for CO_2 emissions (Keller et al. 2021).

Although Deemer et al. (2016) showed that some reservoirs can be CO_2 and nitrous oxide sinks, several other recent studies suggest that reservoirs are a net source of carbon emissions. In their first two to five years of construction, newly formed hydroelectric reservoirs emit almost three to ten times more GHG than natural lakes of the same size; and they continue to release CO_2 and methane during the plant operating lifetime (Fearnside 2006; Tremblay et al. 2005). Considering the additional GHG emissions in the drawdown areas, Keller et al (2021) suggests that hydroelectric reservoirs emit more carbon than they bury.

5.3 Co-benefits and trade-offs regarding freshwater-based mitigation

Freshwater ecosystems provide several important benefits for nature and human society, including provision of food and water, water quality improvement, disaster risk reduction, habitat protection, sediment retention and nutrient cycling, economic, and cultural and recreational benefits (Anisha et al. 2020; de Groot et al. 2008; Doswald and Osti 2011; Dybala et al. 2019). Mitigation measures based on freshwater ecosystems, for example conservation of wetlands or nutrient loading control, can offer some specific direct and indirect co-benefits. However, it is recognized that some socio-economic, socio-political, and development trade-offs would occur if freshwater ecosystems were managed for GHG reduction and increased carbon sequestration. This section highlights possible co-benefits and trade-offs regarding freshwater-based mitigation measures.

5.3.1 Enhancement of ecosystem services through mitigation measures

Burkhard and Maes (2017) define ecosystem services as the contributions of ecosystem structure and function to human well-being. In simple words, ecosystem services are the benefits humans obtain from the ecosystem. The Millennium Ecosystem Assessment (MEA 2005) identifies these services in four broad categories: a) Provisioning services; b) Regulating services; c) Cultural services; and d) Supporting services (see Chapter 3 and MEA 2005). Mitigation measures within freshwater ecosystems, such as pollution control, wetland conservation and restoration, hydrology, vegetation monitoring, etc., (outlined in section 5.2) can enhance the delivery of ecosystem services across all categories. Enhancement of ecosystem services refers to changes in the service that leads to greater benefits for people compared to existing scenarios (MEA 2005). Table 5.3 outlines some examples of how mitigation measures in freshwater ecosystems enhance ecosystem services in different service categories.

Table 5.3. Enhancement of ecosystem services through freshwater-based mitigation measures

ECOSYSTEM SERVICE CATEGORY	FUNCTION	EXAMPLE
Provisioning	Water supply	Pollutant control in rivers and lakes improves the quality of water, which can be used by humans for drinking, swimming, fishing, or other activities (Dosskey 2001; Mitsch 1992). Flooded wetlands play a role in groundwater recharge (Gupta et al. 2020).
	Food	Protected and restored wetlands and well-managed floodplains foster edible plants, shrubs, herbs, and animals (Buckton 2018; Leaman 2018).
	Habitat	Protected and restored wetlands, lakes, and rivers provide a habitat, breeding ground, and refuge for different species of birds, mammals, amphibians, fish, and reptiles (Flores-Rios et al. 2020; Grizzetti et al. 2019).
Regulating	Pollutant control	Protected, restored, and/or constructed wetlands play a role in pathogen removal, and nutrient retention, removal, and breakdown (Vymazal 2018; Mackenzie 2018).
	Disaster risk reduction	Wetland and floodplain protection and expansion can reduce flood risk through enhanced hydraulic connectivity (McInnes 2018a; Tomscha et al. 2021). Coastal wetlands provide protection from storms and coastal erosion (MEA 2005).
	Water quality regulation	Protected and restored wetlands, with healthy vegetation cover, can trap sediments, remove pollutants, and protect rivers and lakes from nutrient overload (Mitsch 1992; Mitsch et al. 2005).
	Erosion regulation	Vegetated wetlands (swamps and marshes) trap sediments and regulate erosion (Fagorite et al. 2019; Ford et al. 2016).
	Microclimate regulation	Wetlands (protected, restored, and constructed) alongside rivers and lakes have a positive effect on the surrounding microclimate with a relative cooling impact (McInnes 2018b; Sun et al. 2012).
Supporting	Biogeochemical cycling	Restored wetlands can store elements such as nitrogen, phosphorus, and carbon for long periods in the soil and supply these elements to surrounding ecosystems; this is unlikely to occur in a drained condition (Everard 2018b; Tomscha et al. 2021).
	Water storage	Water moving through a protected or restored wetland is often slowed by vegetation and this can further promote water retention, infiltration, and storage (Carter 1996; Feng et al. 2021; MEA 2005).
	Hydric soil development	Wetland restoration promotes the development of saturated soil, which enables the growth and regeneration of vegetation adapted to saturated/inundated and low-oxygen conditions (Amon et al. 2005; MEA 2005; Mitsch et al. 2005).
	Biomass production	The nutrients and water retained by floodplains and wetlands aid the growth of vegetation and production of biomass. Wetland restoration supports native plant species diversity (MEA 2005; Tomscha et al. 2021).

ECOSYSTEM SERVICE CATEGORY	FUNCTION	EXAMPLE
Cultural	Recreation	Nutrient and sediment loading control in rivers and lakes can enhance water clarity, which contributes directly and indirectly to recreational benefits, including swimming, boating, fishing, etc. (Angradi et al. 2018).
	Aesthetic	Enhanced water clarity in rivers and lakes can increase visual appeal and improved water quality contributes to enhancement of biodiversity, which adds aesthetic value (Angradi et al. 2018; Papayannis and Pritchard 2018).

5.3.2 Climate change adaptation and resilience benefits from mitigation measures

Ecosystem-based adaptation to climate change, i.e., the synergistic effects of integrating biodiversity and ecosystem services into climate adaptation, has received increasing acknowledgement as a cost-effective, proven, and sustainable solution to climate change adaptation. Freshwater ecosystems are commonly regarded as key components of this approach (Colls et al. 2009; UNEP and IUCN 2021; World Bank 2009). Freshwater-based climate change mitigation measures are based mostly around protecting and restoring water bodies to healthy states. The role of freshwater ecosystems in climate change adaptation has been emphasized due to their ability to persist through climate change effects and continue providing ecosystem services (Colloff et al. 2016; Colls et al. 2009; Lavorel et al. 2015; Morelli et al. 2016). Although climate change is predicted to affect freshwater ecosystems, floodplain ecosystems and well-managed wetlands, even if in a low-diversity state, are likely to persist under climate change and provide adaptation services (Lavorel et al. 2015). In fact, many areas with large water bodies have persisted through the climatic changes of the Holocene, proving their resilience (Morelli et al. 2016). However, there are concerns over whether this can be maintained under changing environmental conditions through the intersection of land-uses and the rapid progression of current climate change.

Climate change is predicted to increase the intensity of extreme precipitation events and the risk of flooding in some parts of the world and intensify drought events in others (Cook et al. 2018; Tabari 2020). Freshwater-based climate change mitigation measures, such as efforts to connect rivers with floodplains, and protect and restore wetlands, are recognized as adaptation measures against increased flood and drought risk (Endter-Wada et al. 2020; Lavorel et al. 2015; Opperman et al. 2009; Vigerstol et al. 2021). Protection or restoration of floodplains has the highest potential to mitigate riverine flood risk since it provides for natural storage and diversion in regularly flooded areas (Vigerstol et al. 2021; Opperman et al. 2009).

Seifollahi-Aghmiuni et al. (2019) highlighted the capacity of well-managed wetlands to retain run-off water and refill aquifers, both of which help minimize drought-induced stress on water reservoirs or stresses that occur due to increased temperatures. Endter-Wada et al. (2020) discussed how riparian wetlands associated with beaver dams can alleviate the impacts of wildfires by creating broad and diffused floodplain habitats that are more resistant to burning. As mean earth temperature rises, the cooling effects created by rivers, lakes, and wetlands provide adaptive services to both humans and animals (particularly in urban areas) (Chang et al. 2007; Costanza et al. 1997; Morelli et al. 2016; Sun et al. 2012).

In an urban setting, wetlands, reservoirs, lakes, and rivers create ‘urban cooling islands’, which maintain lower temperatures in an area compared with its surroundings. In fact, water bodies are relatively more efficient than other types of green spaces due to the higher rate of evapotranspiration (Gober et al. 2010; Hathway and Sharples 2012). Hence, protecting and restoring urban water bodies can bring both mitigation and adaptation benefits. The cooling effect of water bodies enables the creation of climate change refuges for local people, wildlife, and fisheries. In large water bodies and their surrounding areas (deep lakes and wetlands for instance), more solar energy is used in evaporation than in surface heating, which buffers regional warming (Morelli et al. 2016). Protection and restoration of riparian wetlands and forested wetlands can enhance the adaptive capacity of different terrestrial species in a warming climate. The hydrologic connectivity between river and floodplain is regarded as a key predictor of species richness of floodplain invertebrates (Tomscha et al. 2017). This hydrologic connectivity also enhances climate change resilience in many species by allowing movement to new areas when current habitats become unsuitable due to climate change (Cassin and Matthews 2021; Morelli et al. 2016).

5.3.3 Nature-based solutions associated with freshwater ecosystem mitigation measures

Nature-based solutions (NbS) are regarded as sustainable due to their ability to cope with different conditions without greatly altering structure or functionality (robustness). When an environmental condition exceeds a threshold, NbS can be adapted by altering their structure and operating conditions (Folke 2006; Mauroner et al. 2021). Such nature-centric solutions are applicable to different sectors, such as water resources management, disaster risk reduction, water quality control, agricultural technology, and climate change adaptation.

NbS involve advanced and deliberate applications of ecosystem services to meet climate mitigation objectives. Floodplain restoration and management, potentially a freshwater-based mitigation measure, is an effective NbS for flood mitigation, biodiversity protection, and surface water quality control (Acreman et al. 2021; Jakubínský et al. 2021; Keesstra et al. 2018; Perosa et al. 2021). Lo et al. (2021) evaluated the flood mitigation potential of floodplain expansion (called 'Room for the River') compared with three other grey/hard infrastructure solutions (levee extension in variable lengths) on the Nangang River in Taiwan. The authors considered 'Room for the River' to be the best suited flood mitigation measure due to its effectiveness associated with multiple co-benefits compared to grey solutions, which are a single-purpose infrastructure optimized to solve narrowly defined problems (Lo et al. 2021). Perosa et al. (2021) discussed floodplain restoration as NbS for flood protection in three locations of the Danube catchment in Europe and estimated the benefits in terms of monetized ecosystem services. The study estimated a total gain of ecosystem services worth approximately USD 5 million per year in all three locations combined (Perosa et al. 2021). Based on a comprehensive review of over 400 case studies on different NbS across the African continent, Acreman et al. (2021) concluded that floodplain wetlands are effective NbS for flood protection and sediment generation in Africa.

Restored and protected wetlands, even constructed wetlands, are commonly acknowledged as effective NbS for disaster risk reduction, flood management, water quality improvement, and climate change adaptation (Cabral et al. 2017; Keesstra et al. 2018; Liquete et al. 2016; UNEP 2014). In their discussion on the effect of NbS in land management for enhancing ecosystem services, Keesstra et al. (2018) included an example of vegetative sediment trapping measures in Ethiopia where wetlands, along with grassed waterways, were used to trap the sediment in its transport path. This provided solutions for widespread soil loss and sediment overload in the lakes and reservoirs downstream and was deemed superior to other options (Keesstra et al. 2018). Another study in the eastern Free State province of South Africa examined the role of wetlands in disaster risk reduction (such as drought, veld fires, and floods) and concluded that well-managed and protected wetlands are effective buffers and can effectively reduce the risk of veld fires, floods, and drought, whereas degraded wetlands substantially lack risk mitigation capacity. The authors emphasized that restoring degraded wetlands and monitoring the ecological state of protected sites can help to establish wetlands as efficient, cost-effective, community-driven NbS for disaster risk reduction (Belle et al. 2018).

NbS are usually multipurpose, able to address different issues, and aid other solutions or approaches while contributing to the safety, health, well-being, livelihoods, etc. of local populations (Cassin and Matthews 2021). UNEP (2014) outlined some NbS for water resource management and compared them against traditional grey solutions (Table 5.4). In this table, freshwater-based mitigation measures, such as reconnecting rivers to floodplains, wetland conservation/restoration, and constructing wetlands and riparian buffers, are observed as the NbS with the most co-benefits that can address issues regarding water quality regulation, water supply regulation, and extreme weather moderation.

5.3.4 Trade-offs in use of freshwater-based mitigation

The major drivers of wetland degradation and loss include urban expansion and infrastructure development, land conversion to agriculture and

Table 5.4 Nature-based solutions for water resource management

WATER MANAGEMENT ISSUE (PRIMARY SERVICE TO BE PROVIDED)		GREEN INFRASTRUCTURE SOLUTION	LOCATION				CORRESPONDING GREY INFRASTRUCTURE SOLUTION (AT THE PRIMARY SERVICE LEVEL)
			WATERSHED	FLOODPLAIN	URBAN	COASTAL	
Water supply regulation (including drought mitigation)		Re/afforestation and forest conservation	■				Dams and groundwater pumping water distribution systems
		Reconnecting rivers to floodplains		■			
		Wetlands restoration/conservation	■	■	■		
		Constructing wetlands	■	■	■		
		Water harvesting	■	■	■		
		Green spaces (bioretention and infiltration)			■		
		Permeable pavements			■		
Water quality regulation	Water purification	Re/afforestation and forest conservation	■				Water treatment plant
		Riparian buffers		■			
		Reconnecting rivers to floodplains		■			
		Wetlands restoration/conservation	■	■	■		
		Constructing wetlands	■	■	■		
		Green spaces (bioretention and infiltration)			■		
		Permeable pavements			■		
	Erosion control	Re/afforestation and forest conservation	■				Reinforcement of slopes
		Riparian buffers		■			
		Reconnecting rivers to floodplains		■			
	Biological control	Re/afforestation and forest conservation	■				Water treatment plant
		Riparian buffers		■			
		Reconnecting rivers to floodplains		■			
		Wetlands restoration/conservation	■	■	■		
		Constructing wetlands	■	■	■		
	Water temperature control	Re/afforestation and forest conservation	■				Dams
		Riparian buffers		■			
		Reconnecting rivers to floodplains		■			
		Wetlands restoration/conservation	■	■	■		
		Constructing wetlands	■	■	■		
		Green spaces (shading of waterways)			■		
Moderation of extreme events (floods)	Riverine flood control	Re/afforestation and forest conservation	■				Dams and levees
		Riparian buffers		■			
		Reconnecting rivers to floodplains		■			
		Wetlands restoration/conservation	■	■	■		
		Constructing wetlands	■	■	■		
		Establishing flood bypasses		■			
	Urban stormwater runoff	Green roofs			■		Urban stormwater infrastructure
		Green spaces (bioretention and infiltration)			■		
		Water harvesting	■	■	■		
		Permeable pavements			■		
	Coastal flood (storm control)	Protecting/restoring mangroves, coastal marshes, and sand dunes				■	Sea walls
		Protecting/restoring reefs (coral/oyster)				■	

Source: UNEP (2014)

grazing, land-use change, water withdrawal, and pollutant overload (Galatowitsch 2018; Mitsch 2005). The conversion and restoration measures and pollutant control measures that are tied to climate change mitigation may require trade-offs with many of the aspects that have replaced and degraded the wetlands in the first place. In many countries, development is often centred on economic growth along with infrastructure development intended to facilitate growth, and other values are not given a similar priority especially if they are seen to be conflicting. Without the economic values of ecosystem services provided by mitigation measures being considered more commonly, implementing freshwater-based mitigation measures might be perceived as requiring major trade-offs with economic and infrastructural growth (Mauroner et al. 2021; Rozenberg and Fay 2019; World Bank 2012). For example, increasing water flow to a degraded wetland or floodplain for restoration purposes might compete with irrigation water for agriculture (de Groot et al. 2008). Some of the trade-offs and competing interests in implementing freshwater-based mitigation measures are listed below.

- **Trade-offs among the ecosystem services themselves**: As discussed in section 5.2, freshwater-based mitigation measures deliver a wide range of ecosystem services. But many wetlands in the world are valued and utilized mainly for their provisioning services, including food, water, timber, and other products useful to surrounding communities as opposed to the wider spectrum of benefits. The importance of supporting and regulating services can be overlooked by decision-makers, although these services are essential in strengthening the provisioning services received, not just from the wetlands but from the other elements in the ecosystem (such as forests and biodiversity). Mitigation measures, emphasizing the protection and restoration of a healthy ecological state for wetlands, should help support calls to minimize the overexploitation of wetlands, which might seem like a trade-off with how the wetland has been traditionally utilized (Mandishona and Knight, 2022).

- **Trade-offs between floodplain protection and agriculture:** Encroachment of agricultural land into riverine floodplains is common around the world (Pullanikkatil et al. 2020; Verhoeven and Setter, 2010). Protection, restoration, and expansion of floodplain wetlands for climate change mitigation, even with their benefits in sediment retention, water quality improvement, and pollutant control, stand as a trade-off with agricultural expansion, which is critical for present and future food security. Nonetheless, when floodplain wetlands are drained and degraded, their potential to deliver regulating and supporting ecosystem services becomes limited, which might

Migratory birds stop off at the Agamon Hula wetland in north Israel. Source: Shutterstock.

affect agricultural provisioning services. A study conducted on the Hula Wetland in Israel illustrates how degraded wetland conditions can result in declining agricultural production over time (Cohen-Shacham et al. 2011).

- **Trade-offs in urban floodplain restoration:** Floodplains in urban areas are often converted into human settlements, industrial settlements, and recreational facilities, especially since many floodplains have been disconnected from their rivers. Hence, mitigation measures that entail connecting rivers with floodplains and restoration of floodplains can be seen as having trade-offs with the interests of an urban population. Conflict of interest among stakeholders can be minimized if the NbS offered by the mitigation measures can be factored into the cost-benefit analysis and a multifunctional floodplain management approach can be adopted (Jakubínský et al. 2021; Sanon et al. 2012).

- **Trade-offs with community practices and local land-use:** Implementation of mitigation measures might conflict with cultural and social practices. If local communities and stakeholders are not involved fully in communication and collaboration, based upon the principles of free, prior and informed consent, implementation of mitigation measures is likely to meet resistance. Conservation can also limit access to the freshwater ecosystem and its services for indigenous peoples and local communities. This conflict of interests can be minimized by effective communication, education, inclusion, and multisectoral collaboration (Boughton et al. 2019; Dahlberg and Burlando 2009).

- **Trade-offs between wetland restoration and biodiversity:** Factors influencing freshwater-based mitigation measures include nutrient cycling and control, soil organic matter, biomass, decomposition rates, and potential denitrification (section 5.2). But restoring wetlands for carbon and nutrient storage and removal might not be favourable for biodiversity in all cases. In fact, it should not be expected that all ecosystem services would be maximized at a restoration site (Jessop et al. 2015; Peralta et al. 2017). A study conducted on a restored wetland in the USA suggested sites with less biodiversity had greater soil organic matter, biomass, decomposition rates, and denitrification potential (Jessop et al. 2015).

5.4 Policy status

Many countries in the world have policies to address the conservation, restoration, or management of wetlands, but less attention has been paid to other aquatic ecosystems. There are international agreements (e.g., treaties, conventions, and protocols) in place to ensure shared understanding of sustainable management of wetlands and to shape actions that can protect the wetlands and the ecosystems surrounding them. The Ramsar Convention on Wetlands of International Importance especially as Waterfowl Habitat, commonly known as the Ramsar Convention on Wetlands, is the longest established intergovernmental environmental agreement and the most relevant to wetlands internationally with 172 parties (nations or states) as signatories as of 2023 (Ramsar Convention 2016, Ramsar Convention 2023). According to the Ramsar Convention definition of wetlands, all freshwater ecosystems (including rivers, streams, lakes, reservoirs, etc.) are wetlands. This section discusses how freshwater-focused climate mitigation measures have been included in the Ramsar Convention and some countries' national policies.

5.4.1 Ramsar Convention on Wetlands of International Importance

As a multilateral environmental agreement, the Ramsar Convention provides a framework for national action and international cooperation on the conservation and wise use of wetlands and their resources (Finlayson 2012). Initially, the Ramsar Convention had its emphasis on the conservation and wise use of wetlands as a habitat for waterbirds (Ramsar Convention 2005). (Wise use of wetlands is the maintenance of their ecological character, achieved through the implementation of ecosystem approaches within the context of sustainable development.) The Convention has broadened its scope of implementation over the years, now addressing wise water use for enhanced ecosystem services, sustainable development, and biodiversity conservation, in addition to wetland conservation (Ramsar Convention 2016). While the ecosystem services provided by wetlands have been repeatedly addressed in the convention, the role of wetlands in climate regulation was highlighted much later in the process. Until 2008, the Ramsar Convention strategic plans did not address the importance of wetlands as carbon sinks (Ramsar Convention

1996). The Briefing Note 4 provided by the Ramsar Convention in 2012 acknowledged carbon sequestration as one of the key benefits of wetland restoration and the Ramsar Strategic Plan 2009–2015 emphasized the role of wetlands in climate change mitigation (Ramsar Convention 2008; Ramsar Convention 2012). Whether or not wetland-based climate mitigation was highlighted, the Ramsar Convention emphasis on wetland conservation and restoration throughout the years can be considered as an indirect but effective measure in supporting the role of wetlands in climate change mitigation.

In the latest strategic plan (Resolution XII.2: The Ramsar Strategic Plan 2016–2024), the Ramsar Convention mentioned restoration of wetlands for their role in climate change mitigation and adaptation as one of the targets to achieve the strategic goal of wise use of all wetlands (Ramsar Convention Secretariat, 2015). In Briefing Note 10, published in 2018, the wise use and restoration of wetlands is identified as "essential to protect stored carbon and reduce avoidable carbon emissions" (Ramsar Convention Secretariat, 2018). In the latest two Global Wetland Outlook reports (published in 2018 and 2021), the importance of wetland conservation and restoration for climate change mitigation, mostly in peatlands and coastal 'blue carbon' ecosystems, was highlighted. The Ramsar Convention provides detailed guidelines on the management and restoration of both peatlands and 'blue carbon' systems to enhance their climate mitigation potential (Ramsar Convention 2018; Ramsar Convention 2021).

Wetland conservation and restoration are essential to utilize their potential in climate change mitigation. For example, drained peatlands stop sequestering carbon and lose previously stored carbon through decomposition processes for a long period of time resulting in GHG emissions. Rewetting or restoring wetlands, particularly peatlands, can significantly reduce CO_2 emissions (also other GHGs) and may reinitiate carbon sequestration, but rewetted peatlands might not return to the undisturbed natural conditions that allow high climate mitigation potential even within decades. Hence, conservation of these wetlands is to be prioritized to avoid additional emissions, and restoration is to be prioritized to reduce emissions and enhance carbon sequestration (Kreyling et al. 2021; Günther et al. 2020; Joosten 2015). For years, the Ramsar Convention's efforts in global wetland conservation and restoration played a big role in protecting the carbon pools in wetlands. Although Ramsar identifies rivers, streams, lakes, and reservoirs as wetlands, there are no obvious guidelines to minimize emissions from these systems.

5.4.2 National policies

National-level policies on wetlands have the capacity to outline goals related to wetland management, timelines for achievement of those goals, roles and responsibilities of various actors, and budget commitments (Gardner 2018b). The Ramsar Convention recommends that parties develop national wetland policies to implement the Convention at national and regional levels (Ramsar Convention Secretariat 2015; Ramsar Convention Secretariat 2010; Bonells 2018). While some countries have wetland-specific national policies, others include wetland-related policies under broader environmental policies or land-use and water-use policies. Peimer et al. (2017) examined wetlands policies in 193 countries and found that only 9 per cent have an existing wetland-specific policy; 38 per cent have a broad environmental policy or law that includes wetlands; 18 per cent have a wetland policy in development; and 23 per cent have no national-level environmental policy or strategy to protect wetlands.

Wetland-specific national policies can be important in protecting and managing wetlands and ensuring they maintain their role in climate change mitigation (Peimer et al. 2017). For example, the adoption of a national wetlands policy in Uganda in the early 1990s paved the way for inclusion of wetlands in many other national policies and eventually included them in Uganda's updated Nationally Determined Contributions (NDC) for 2021–2030. The updated NDC includes wetlands under one of the key sectors of agriculture, forestry, and other land-use for mitigation (Mafabi 2018; Ministry of Water and Environment, Uganda, 2021; also see Chapter 3). This is one of the few examples of wetlands inclusion in the first round of NDCs. Chile also developed a national wetlands strategy in 2005; this enables coordinated and efficient protection of wetlands and aligns with the country's national biodiversity strategy. To achieve one of the objectives of the strategy, the country has created a national wetlands inventory (Suárez-Delucchi 2018). As per Chile's latest NDC updates, the country now considers wetlands in its mitigation strategy (See Box 5.2).

Wetlands restoration project at Libertyville, Illinois, USA. Source: Shutterstock.

In the USA, wetlands are included in several different broad environmental policies, management plans, acts, regulations, and even executive orders. The USA adopted the 'No net loss' policy (a policy also adopted by the European Union) for wetland preservation in 1989 with the goal to balance wetland loss with replacement wetlands, mainly through reclamation, mitigation, and restoration to maintain the total areal coverage of wetlands in the country (Everard 2018a). The policy showed promising results in the initial years, but 62,300 acres of wetland was reported lost from 2004 to 2009 (Smaczniak 2018). One of the key measures of 'No net loss' is wetland offsets, also called compensatory wetlands, which entails creation or restoration of wetlands of at least the same area as that lost (Fennessy and Dresser 2018). As these compensatory/replacement wetlands may be significantly different from the natural wetlands in character and function, their role in climate change mitigation also may vary (BenDor and Riggsbee 2011; Everard 2018b; Fennessy and Dresser 2018; Neubauer and Verhoeven 2019). Neubauer and Verhoeven (2019) maintain that GHG emissions from disturbed wetlands persist long after a wetland is restored or replaced by a mitigation wetland. Hence, from a climate change mitigation perspective, stronger priority should be given to protecting existing natural wetlands (Neubauer and Verhoeven 2019).

Wetland-specific national policies should emphasize wetland conservation, restoration, and wise use. But if nations are considering wetlands for climate change mitigation, this needs to be reflected in their NDCs as well as in national and local policies with quantitative emissions targets. Wetland-related measures should be considered as an integral part of an NDC (Anisha et al. 2020). Box 5.2 illustrates some examples of wetland-centric mitigation measures in NDCs. Inclusion of freshwater-related policies in national-level documents, such as National Adaption Plans, National Biodiversity Strategies and Action Plans, and Integrated Coastal Zone Management can lay the groundwork for NDCs and vice versa in the future.

Box 5.2. Integration in NDCs

Freshwater and tidal wetlands were included in most of the enhanced NDCs that were prepared in the two years prior to January 2022. Within Annex 1 countries, references to wetlands are mainly noted through recognition within land use, land use change, and forestry category targets, although parties such as Canada and Iceland included actions to restore wetlands as part of their measures. Freshwater ecosystem measures, including protection, rehabilitation, and enhancement activities are more commonly found within updated NDCs from non-Annex 1 parties, including both adaptation and mitigation. In the first round of NDCs, only seven non-Annex 1 parties included measures relating to wetlands, most notably Uganda, and most of these were related to adaptation, although Uganda did include some measures within its mitigation section. Similarly, in the first round, only a few countries, most notably the Bahamas, noted the role of mangrove swamps as a carbon sink and their ecological functions.

In comparison, a total of 65 non-Annex 1 countries (57 per cent), out of 114 non-Annex 1 NDCs released between 2019 and 2022 have included wetland measures in their enhanced NDCs, with a further 4 including wetlands within their inventories. Most of these wetland measures are adaptation priorities, but recognition of the role of wetlands in mitigation or in integrated mitigation and adaptation increased significantly. Approximately 18 non-Annex 1 parties included specific wetlands mitigation measures (16 per cent of the total), and 25 countries included mangrove forests specifically in their mitigation priorities, noted mainly as 'blue carbon' priorities. Of note are measures by the Democratic Republic of the Congo with respect to the important role of peatlands nationally and globally, especially regarding emissions reductions. Measures for wetlands found in mitigation sections were much less detailed when compared with measures found in adaptation sections.

Acknowledgement of the role of mangrove ecosystems in both mitigation and adaptation was much greater in enhanced NDCs compared with previous versions, most notably from Belize and Colombia. Forty-nine countries included mangroves within their respective enhanced NDCs, including close to 62 per cent of those countries hosting mangrove ecosystems, but as above, a smaller number included mangrove measures within their mitigation sections.

The potential role of other water-related ecosystems such as rivers or lakes in mitigation was not directly found in any enhanced NDCs, despite recent research suggesting that overly degraded systems may be a strong source of emissions. However, water pollution through inadequate wastewater management, and its impact on freshwater ecosystems and their capacity to provide ecosystem services, was noted in many adaptation sections, and was much more prominent compared with the first round of NDCs.

Examples of mitigation measures include:

- **Belize:** Enhance the capacity of the country's mangrove and seagrass ecosystems to act as a carbon sink by 2030, through increased protection of mangroves and by removing a cumulative total of 381 kilotons of CO_2 equivalent (Kt CO_2-e) between 2021 and 2030 through mangrove restoration.
- **Sierra Leone:** Organic manure to reduce fertilizer use that has the tendency of depleting soil fertility and polluting wetlands.
- **South Sudan:** Conservation and sustainable use of wetlands for improved carbon sequestration. South Sudan will collaborate with international research institutes and agencies to conduct research on the release of methane emissions from the Sudd wetland and develop measures to sustainably manage and mitigate high emissions coming from the country's wetlands.
- **Uganda**: The measure aims to increase wetland coverage from 8.9 per cent in 2020 to 9.57 per cent in 2025, and approximately 12 per cent by 2030 through the implementation of wetland management practices such as demarcation, gazettement, and restoration of degraded wetlands. The mitigation reduction potential for this measure is expected to account for 0.4 Mt CO_2-e by 2030.

Background to the NDCs is found in Chapter 3.

Source: UNDP-SIWI Water Governance Facility (2023).

5.5 Potential implications for governance

5.5.1 Inclusion in national policies

Section 5.4.2 illustrates the importance of having national policies on wetlands to promote wetland-focused climate change mitigation measures. Uganda and Chile (cases mentioned previously in this chapter) demonstrate a clear example of this. Wetland-specific national policies should emphasize wetland conservation, restoration, and wise use. But whether or not nations are considering wetlands or other freshwater ecosystems for climate change mitigation is reflected in their NDCs. Freshwater-related mitigation measures should be considered as an integral part of NDCs (Anisha et al. 2020). However, inclusion of freshwater-related policies in national-level documents, such as National Adaption Plans, National Biodiversity Strategies and Action Plans, and Integrated Coastal Zone Management can lay the groundwork for NDCs.

5.5.2 Systems-level approach

Many of the mitigation measures outlined in section 5.2 are applicable to freshwater ecosystems. For example, nutrient control benefits rivers, lakes, reservoirs, and other wetlands for climate change mitigation, as GHG production in aquatic systems is fuelled mainly by inputs from the watershed. Effective emissions reduction strategies should entail coordinated approaches for land management, restricting nutrient loading, and maintaining and improving ecohydrological connections. Inland water bodies constantly interact with other components of the ecosystem (vegetation, landform, biodiversity, and humans) and among themselves through subsurface flow, groundwater flow, ecohydrological connectivity, and sediment and organic matter exchange. Hence, mitigation benefits cannot be sustainably materialized if the activities are undertaken in isolation. System-level approaches on a local, sub-regional, or regional level can minimize the potential trade-offs among different interests. This requires inter-sectoral coordination and policy synergies. Management and planning ought to consider the different scales at which socio-ecological systems might interact with freshwater ecosystems and make sure the dynamics are sustainable.

5.5.3 Implications of future climate change

Climate change is predicted to affect freshwater ecosystems, but floodplain ecosystems and well-managed wetlands, even those in a low-diversity state, are likely to persist under climate change and provide adaptation services (Lavorel et al. 2015). In fact, many areas with large water bodies have persisted through the climatic changes of the Holocene, proving their resilience (Morelli et al. 2016). It is uncertain though, whether the freshwater ecosystems would persist with the same characteristics that enable them to sequester carbon over long periods of time (Sutfin et al. 2016; Yan et al. 2021). For example, higher rainfall due to climate change will increase flushing and delivery of soil and riparian/wetland carbon to streams and rivers, resulting in higher GHG emissions. Peatlands will release more carbon if drought conditions prevail. Tidal wetlands will be affected by sea-level rise. Hence, planning should not be based on historic or present trends but should take future climate change scenarios into consideration. Developing an understanding of how ecosystems might transform under climate change can assist in adopting measures that can be adapted as conditions change.

5.5.4 Implication of socio-economic change

As discussed in section 5.2, anthropogenic activities have disturbed the carbon pool in freshwater ecosystems and increased GHG emissions, and probably will continue to do so. For example, societal choices will determine the future total nitrogen loading in a freshwater ecosystem. The future global population and its socio-economic choices will determine global demand for food and agriculture, bioenergy, assumptions about trade, and assumptions about agricultural management practices, which will eventually determine the total nitrogen loading in freshwater ecosystems, although practices might vary regionally (Sinha et al. 2019). The planning and management of freshwater-based mitigation measures should consider these socio-economic changes for successful implementation.

5.6 Conclusions and outlook

Historically, the climate change mitigation potential of freshwater ecosystems has been highly underrated. Although freshwater marshes, swamps, and peatlands have been included regularly in recent discussions (but not yet sufficiently), the management of rivers, lakes, and reservoirs is still not reflected in important national policies (e.g. NDCs). Freshwater ecosystems have generally been considered as carbon neutral or carbon sinks, which is true for most of these ecosystems before being exposed to anthropogenic disturbances. However, freshwater ecosystems in most parts of the world have been subjected to some kind of disturbance, which imposes a risk of those systems becoming net sources of GHG emissions. Every signatory party under the Paris Agreement has some potential to include freshwater-based mitigation targets in their NDCs and it is essential that inclusion of freshwater ecosystems is mainstreamed.

Freshwater ecosystems also need to be included within GHG inventories. To achieve this, global datasets and reporting methods for freshwater ecosystem health and coverage should be strengthened through both policies and financing mechanisms. In particular, countries need to be incentivized to develop robust inventories of aquatic ecosystems that can be used to safeguard biodiversity and ecosystem services, including the mitigation of GHG emissions. It is also critical to facilitate the development of measurement technologies, especially in contexts where conventional measurement techniques cannot be used, to acquire standardized global data sets targeting long-term, continuous, large-scale data that can be measured simply and at low cost.

For successful water-wise climate mitigation in freshwater ecosystems, governance across all levels needs to be strengthened. Possibilities to align the NDCs with other policies, such as National Adaption Plans, National Biodiversity Strategies and Action Plans, and Integrated Coastal Zone Management, should be explored.

Okavango Delta, a UNESCO World Heritage Site and Ramsar Site, Botswana, Africa. Source: Shutterstock.

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CHAPTER 6

Mitigation measures in land systems

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Chapter 6 Contents

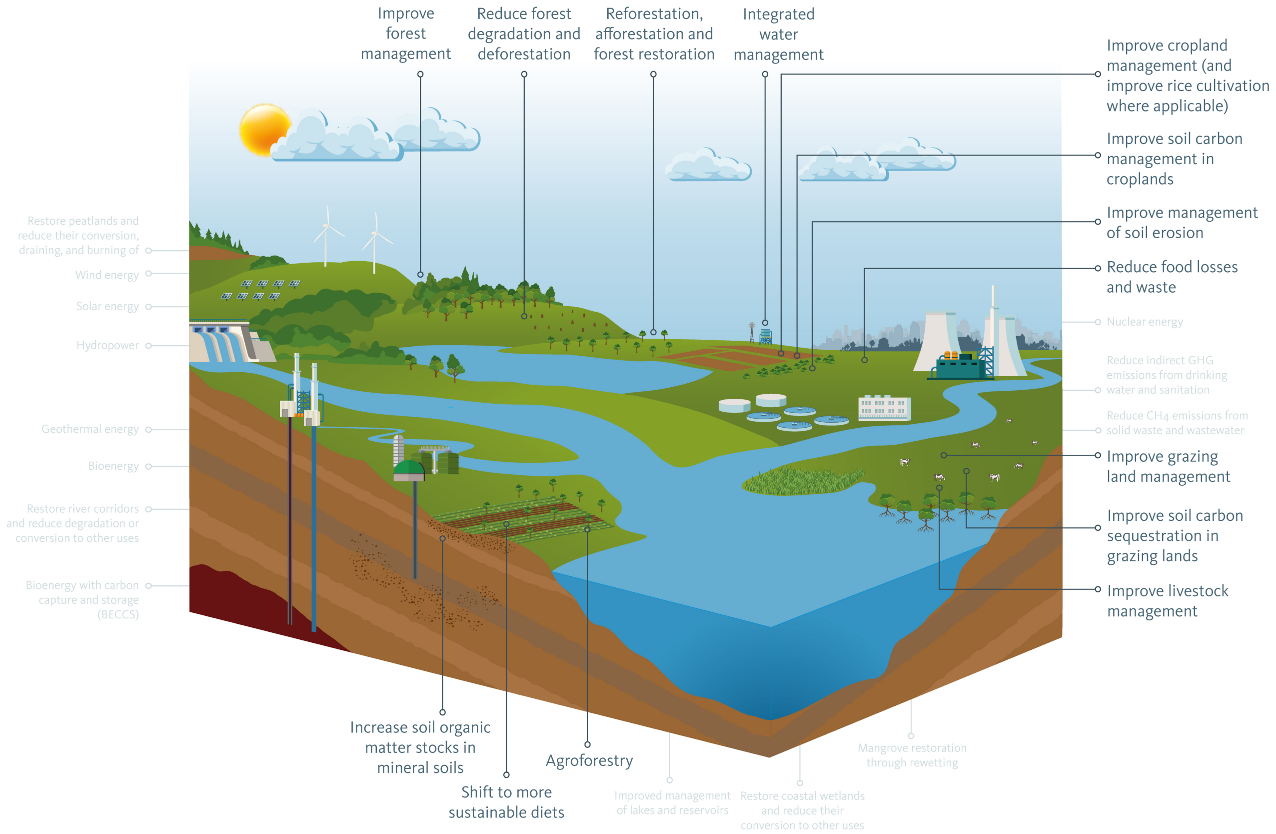


Figure 6.0. Mitigation measures in land systems. Source: SIWI.

Highlights

- Climate mitigation measures in land systems are an important means of protecting existing carbon sinks and binding carbon to soil, and to below- and above-ground biomass, in land-based ecosystems. The success of climate mitigation in land systems depends substantially on water availability and dynamics, which are prone to unpredictable and unfavourable variations under current and future environmental changes.
- Climate change has already altered water cycles in many land systems to a significant extent and the strength of the carbon sink effect appears to be declining in some terrestrial ecosystems, including some tropical forests.
- Halting deforestation and forest degradation in major forest biomes helps to preserve favourable water cycle dynamics at the continental, planetary, and intergenerational scales. Forest biomes are of key importance for the regulation of the Earth's energy, water, carbon, and nutrient cycle dynamics. Continued deterioration of the regulating effect of forests on the water cycle risks lowering agricultural productivity regionally and globally, as well as converting forest carbon sinks into carbon sources.
- Mitigation in natural grasslands, pastures, and croplands depends primarily on improved water management. This includes reducing soil erosion by water by adopting agroecological methods such as agroforestry, which can protect and improve below- and above-ground carbon stocks.
- Mitigation measures in land systems can have notable synergies and trade-offs with local- to regional-level water sustainability goals. Conservation, restoration, and sustainable land and forest management have the potential to decrease flood risk, increase groundwater recharge, and increase water vapour exchange with the atmosphere, thereby enhancing local cooling and boosting regional rainfall. However, misguided implementation of mitigation measures can cause local water shortages, biodiversity loss, and harm to local communities.

6.1 Introduction

Climate mitigation in land systems can be focused on three main actions: i) reduce emissions from agriculture, forestry, and other land-use systems; ii) enhance the capacity of ecosystems and agroecosystems to sequester carbon; and iii) protect existing greenhouse gas (GHG) sinks in such ecosystems as forests, wetlands, peatlands, and soils. The Intergovernmental Panel on Climate Change (IPCC 2022) estimates that land systems could provide 20 to 30 per cent of the mitigation required to ensure global warming stays at less than 1.5°C above pre-industrial levels.

The mitigation potential of land systems is connected intimately with and depends on the water cycle. Healthy ecosystems and sustainably managed land systems rely on stable access to freshwater and reliable weather cycles. However, many of the world's forests, grasslands, and agricultural systems are in poor condition and suffer from unsustainable management, leading to disturbed water cycles, biodiversity loss, and land degradation, which also exacerbate climate change. Interactions between the impacts of climate change and land degradation can influence the capacity of soil to store carbon and act as a carbon sink. Thus, measures to reduce land degradation also have positive impacts on climate mitigation (Figure 6.1.).

At the same time, climate change can exacerbate many degradation processes and introduce new ones (such as thawing of permafrost or biome shifts); this is an important consideration in climate mitigation strategies (IPCC 2019). In croplands, increased decomposition usually leads to reduced soil organic carbon, which also negatively affects soil productivity and carbon sinks. In tropical forests, a drier hydroclimate and deforestation are causing reductions in net carbon uptake.

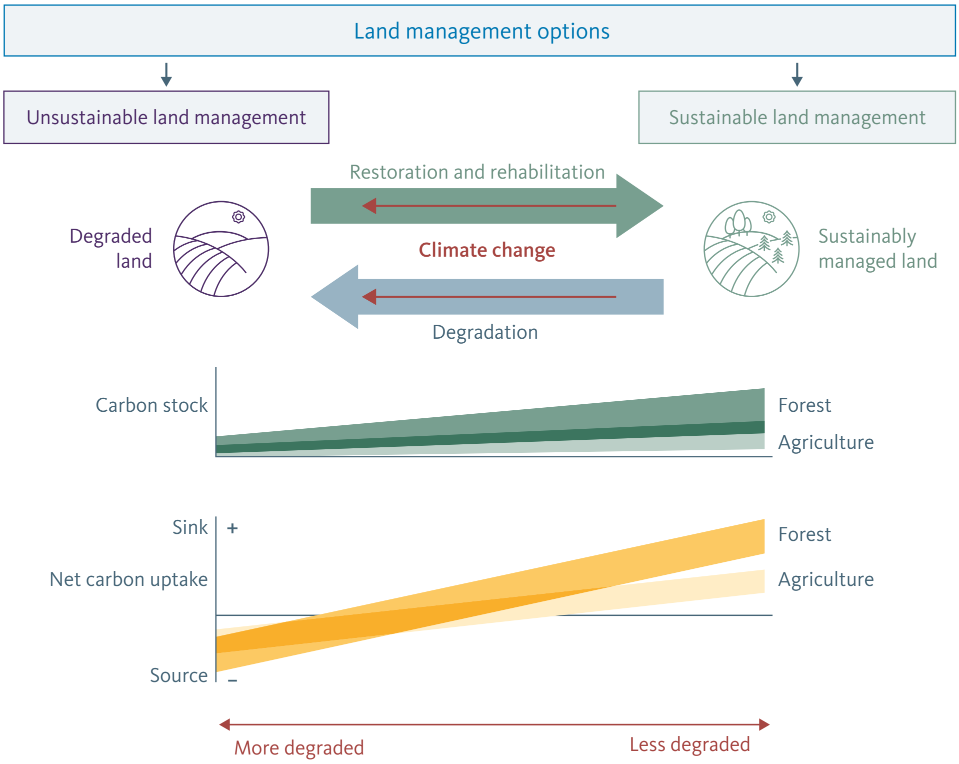


Figure 6.1. Conceptual illustration of interactions between the impacts of climate change and land-use management, and how these influence the capacity of soil to store carbon and act as a carbon sink. Source: IPCC (2019).

In addition, agriculture, forestry and other land use (AFOLU) is the only sector in which mitigation via large-scale carbon dioxide (CO_2) removal (e.g., through afforestation/reforestation or soil organic carbon management) may be possible currently and in the short term (IPCC 2022). Such 'negative emissions' (i.e., net CO_2 removal) from ecosystems are part of all IPCC scenarios that limit global warming to 1.5°C (Masson-Delmotte et al. 2022). Over 90 per cent of AFOLU emissions result from agricultural practices, with an estimated mitigation potential of 4.1 gigatons of CO_2 equivalent ($GtCO_2$-e) per year through measures taken across the sector over the next three decades (IPCC 2022). Given its considerable potential, land-based mitigation can and should be an essential component of Nationally Determined Contributions (NDCs) under the Paris Agreement (see Box 6.7 in section 6.6.1.).

There is strong evidence that climate mitigation in land systems can be effective from a biophysical and ecological perspective. However, to date, the AFOLU sector globally has contributed only modestly to net reductions (about 0.65 $GtCO_2$ per year of reduction from 2010 to 2019, or 1.4 per cent of global emissions). This is due mainly to governance challenges relating to a lack of institutional support, and fragmented and unclear land ownership (IPCC 2022). In addition, mitigation measures may lead to increased competition for water and agricultural land, issues with implementation and permanence, particularly in countries with weak governance (Doelman et al. 2020), and other adverse social impacts associated with land rights, and blue and green water availability, for example. Over 70 per cent of freshwater withdrawals are used for irrigation in agriculture and, by 2050, an estimated 15 per cent increase in water withdrawals is expected (Khokhar 2017). At the same time, about 80 per cent of the world's cropland is entirely rainfed. Land management measures here are particularly susceptible to the impacts of drought induced by climate change. Globally, over 80 per cent of all drought impacts occur in the agricultural sector. There is therefore a need to plan for and implement land management measures that can contribute to both mitigation and adaptation to climate change using integrated approaches that have the potential to synergistically address today's multiple environmental challenges while also improving governance structures (IPCC 2019; Pörtner et al. 2021; also see Chapter 9).

Improved cropland management, conservation and restoration of soils, and restoration of degraded land for climate mitigation may lead to enhanced resilience. There are also several co-benefits, such as reliable access to freshwater, enhanced biodiversity, improved farm production, poverty alleviation, and social development. Implementing these measures may also lead to trade-offs associated with competition for land, for example between farmers and pastoralists where pastoralists' access to grazing lands becomes reduced (Behnke 2018).

In this chapter, we examine the potential and water-related risks of land system climate mitigation measures (section 6.2), focusing on forests, grasslands, pastures, and croplands. Sections 6.3 and 6.4 map the extent of the dependence and impact on the water cycle and freshwater resources of land system climate mitigation measures. Section 6.5 addresses the co-benefits and trade-offs with human well-being and social development goals. Section 6.6 presents the current policy status, and section 6.7 elaborates on the potential implications for governance. The chapter concludes in section 6.8 with an outlook for the future.

6.2 Mitigation potential in land systems

The selection of mitigation measures addressed in this chapter is based on: i) the estimated mitigation potential following the categories of IPCC (2019) (see Table 6.1); and ii) the level of impact on or demand for freshwater. Based on these criteria, the chapter focuses on the following measures: reforestation/afforestation and forest restoration; reduced deforestation and forest degradation; improved forest management; improved carbon management and soil carbon sequestration in croplands, agroforestry, and grasslands; and reduced methane emissions through improved rice cultivation. In this context, it is also important to highlight mitigation measures linked to dietary shifts and reductions in food loss and waste. These measures hold high potential to mitigate climate change but have a low direct impact on or demand for freshwater. The issues of dietary shifts and food loss and waste are addressed further in Chapter 8.

Land-based ecosystems absorbed around 30 per cent of the carbon emissions generated through human activity in the last decade, while land systems also contribute to a quarter of global GHG emissions (IPCC 2022). For instance, it has been shown that land use has a large negative impact on the potential amount of carbon that can be stored in terrestrial biomass (Erb et al. 2018) (Figure 6.2). Thus, with climate-smart management, land systems have great mitigation potential not only in natural ecosystems, but also in agricultural lands, productive forests, and other production systems. Conservation, restoration, and sustainable management of land-based ecosystems and production systems are important climate mitigation measures (see Table 6.1), while also supporting local water cycles, biodiversity and local communities. In addition, halting deforestation and forest degradation in major forest biomes helps preserve favourable water cycle dynamics at the continental to planetary and intergenerational scales, such as atmospheric moisture regimes and precipitation patterns.

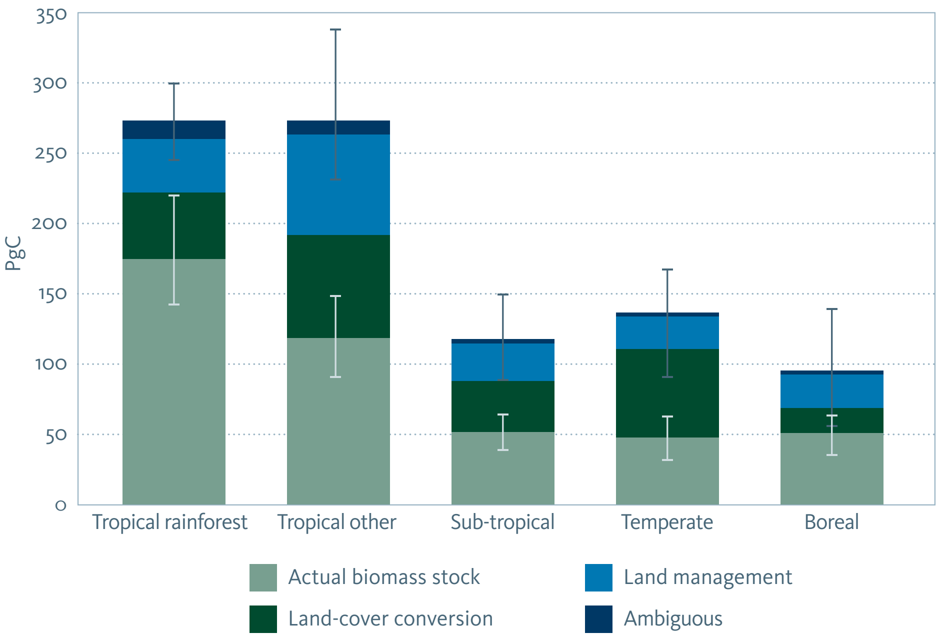


Figure 6.2. Actual biomass stocks in the world's major biomes, as well as the potential role of land-cover conversion and management to potential biomass stocks. Whiskers indicate the range of the estimates for potential (black; n=6) and actual (grey; n=7) biomass stocks. Source: Erb et al. (2018).

Table 6.1. Climate mitigation measures in land systems with high estimated mitigation potential

MITIGATION MEASURE IN LAND SYSTEMS	MITIGATION POTENTIAL GTCO$_2$-E PER YEAR 2020-2050	CONFIDENCE LEVEL
Reforestation, afforestation, and forest restoration	1.50–10.10	medium
Increase soil organic matter stocks in mineral soils	0.40–8.64	high
Shift to more sustainable diets*	0.70–8.00	high
Improve soil carbon management in croplands	0.25–6.78	high
Reduce deforestation	0.41–5.80	high
Agroforestry	0.11–5.68	medium
Reduce food losses and waste*	0.80–4.50	high
Improve management of soil erosion	0.44–3.67	-
Improve soil carbon sequestration in grazing lands	0.13–2.56	high
Improve livestock management*	0.20–2.40	medium
Improve cropland management	1.40–2.30	medium
Reduce forest degradation	1.00–2.18	high
Improve forest management	0.44–2.10	medium
Improve grazing land management	1.40–1.80	medium
Improve rice cultivation (reduce methane)	0.08–0.87	-
Improve water management	0.1–0.72	-

* Climate mitigation measures that have indirect impact on or demand for freshwater. Source: IPCC (2019)

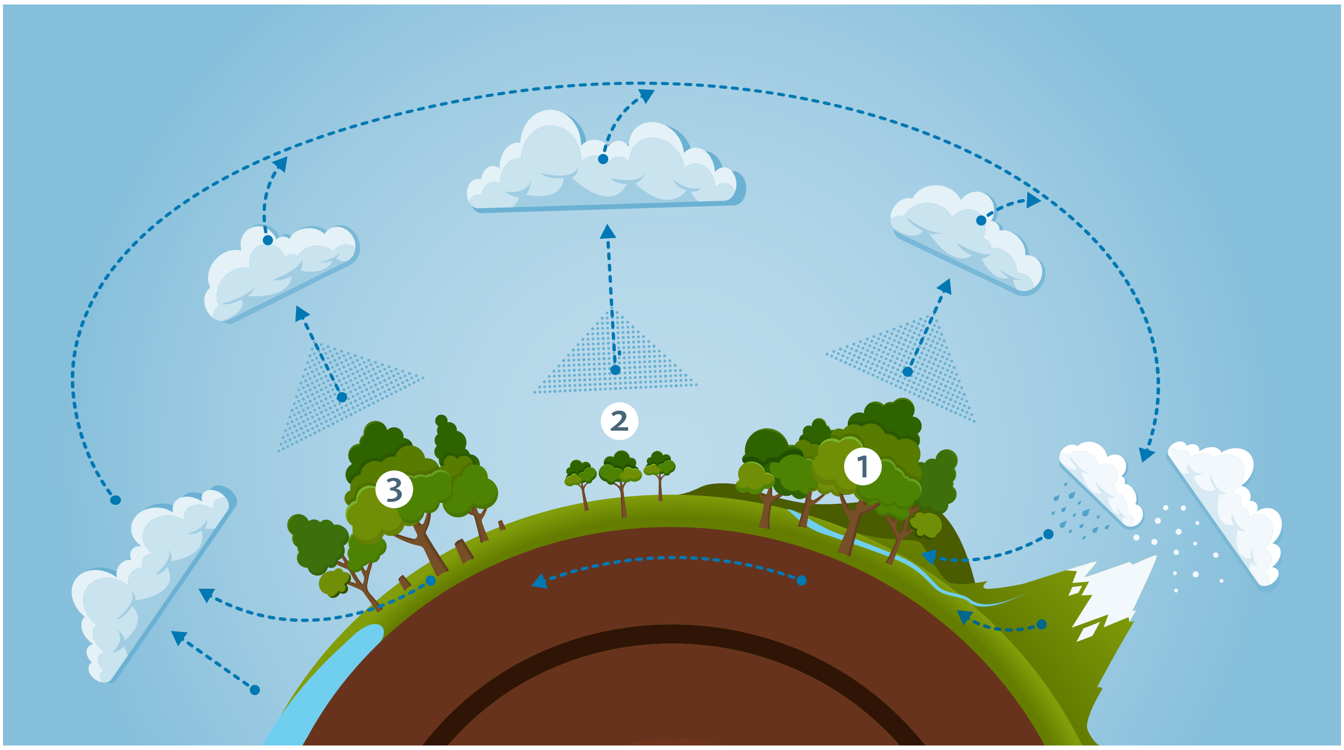
6.2.1 Mitigation potential in forests

Forests are well known to be carbon sinks, and many governments have advanced plans to plant vast numbers of trees to absorb CO_2 from the atmosphere in an attempt to slow climate change (Popkin 2019). However, the success of forest mitigation measures relies substantially on the water cycle, in particular, reliable precipitation patterns and freshwater availability. Forest mitigation measures, including reducing deforestation and forest degradation; reforestation, afforestation, and restoration; and improved forest management are highly dependent on the water cycle, while also impacting it (Figure 6.3). Forests and trees are key elements of the water cycle and have an impact on many water cycle processes and functions, including atmospheric moisture transport, infiltration and groundwater recharge, flood moderation, fog/cloud interception, and precipitation recycling at regional and continental scales (Sheil et al. 2019; Ellison et al. 2017; Ilstedt et al. 2016).

Reducing deforestation and forest degradation

Reducing deforestation and forest degradation is estimated to have a mitigation potential of 1.41–7.98 GtCO$_2$-e per year over 2020–2050 (IPCC 2019). Globally, these measures also have a high potential for climate and water sustainability win-wins; for instance, in supporting healthy water cycles, safeguarding biodiversity, and enhancing the resilience of local communities and urban areas. Primary and old secondary forests are particularly important carbon sinks, as well as regulators of regional water cycles and climatic patterns (e.g., Luyssaert et al. 2008; 2018). Natural forests can be up to six times more effective at storing carbon than agroforestry, and up to 40 times more effective than tree plantations (per unit area until 2100) (Lewis et al. 2019). However, there are concerning signs of increased carbon losses due to drought-induced tree mortality and subsequent carbon sink saturation in tropical forests (Green et al. 2019; Hubau et al. 2020), as well as substantial risks for crossing deforestation tipping points beyond which self-amplifying feedback loops push the biomes towards alternative stable non-forest states (Staal et al. 2020; Zemp et al. 2017).

Tropical forests account for half of the global terrestrial vegetation carbon storage (Lewis, Edwards, and Galbraith 2015). Existing forests sequester 15.6 ± 49 GtCO$_2$-e per year, while in recent decades



① Mitigation measure 1 – Reducing deforestation and forest degradation

② Mitigation measure 2 – Reforestation, afforestation, and restoration

③ Mitigation measure 3 – Forest management

Fig. 6.3. Conceptual overview of forest systems mitigation measures and their impacts on the water cycle. Source: SIWI.

under elevated atmospheric CO_2 concentration, deforestation and forest degradation emitted 8.1 ± 2.5 $GtCO_2$-e per year (Harris et al. 2021). Furthermore, long-term measurements suggest that the tropical rainforest carbon sink strength, i.e., the ability of the forest to absorb more carbon than it releases, has already peaked (since the 1990s in the Amazon and more recently in African rainforests), due primarily to negative drought and temperature impacts on tree growth and mortality (Hubau et al. 2020) (Figure 6.4). Due to a combination of forest area loss, falling carbon sink strength per forest unit area, and rising anthropogenic carbon emissions, the fraction of anthropogenic CO_2 emissions removed by tropical forests has fallen from 17 per cent in the 1990s to just 6 per cent in the 2010s (Hubau et al. 2020). The carbon sink strength will continue to decline, with the magnitude depending to some extent on the severity of future deforestation and emissions scenarios (Hubau et al. 2020). Nevertheless, Earth system model-based projections, which inform policy- and decision-making, appear to predict a weak increase in forest carbon sink strength, contrary to the observation-based prediction of future decreases (Koch, Hubau, and Lewis 2021). Thus, to continue to benefit from the tropical forest carbon sinks, it will be critical to prevent forest loss and human-induced fire disturbance, protect the forest water cycle, and enact a rapid halt to anthropogenic GHG emissions. The altitude of the forest may also have an impact on the carbon storage capacity. Recent findings show that the carbon sink strength of Andean rainforests is higher for lowland than for highland rainforests (Duque et al. 2021); while montane forest sites in Africa could hold two-thirds more carbon than IPCC has estimated for those areas (Cuni-Sanchez et al. 2021).

In temperate forests, the net CO_2 sink has increased in recent decades due to warming-induced changes in phenology (Keenan et al. 2014) and CO_2 fertilization (Walker et al. 2021). However, this trend appears to have recently slowed due to a weakening temperature control of spring carbon uptake (Piao et al. 2018) and a declining CO_2 fertilization effect on vegetation photosynthesis (Wang et al. 2020).

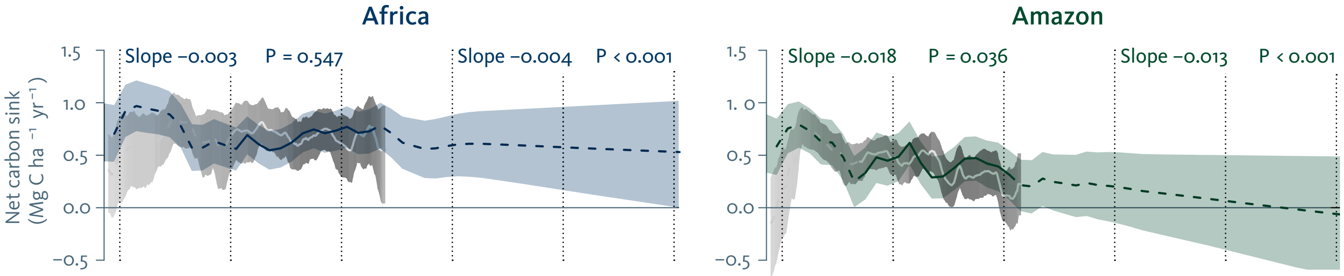


Figure 6.4. The net carbon sink - i.e., the ability of the forest to absorb more carbon than it releases - has already peaked in both the African and the Amazonian forest and is projected to continue to decline. Source: Hubau et al. (2020).

Reforestation, afforestation, and forest restoration

These are the mitigation measures estimated to have the highest climate mitigation potential globally (up to >10 GtCO$_2$-e per year over the years 2020–2050) (IPCC 2019). These measures can considerably impact the water cycle (Hoek van Dijke et al. 2022). Under favourable conditions, increased tree cover can increase precipitation, water yield, and soil infiltration capacity, contributing to a reduction in both flood and drought risk (Teo et al. 2022). Under unfavourable conditions, increased tree cover can be associated with negative impacts on streamflow, reduced flows to wetlands, and dwindling water tables (Filoso et al. 2017). The higher levels of mitigation potential can only be realised with a high level of water use (including irrigation demand) and with a substantial risk of disruption to the local hydrological balance (such as through streamflow decrease and the lowering of groundwater tables). This is particularly important in cases where water is a limiting factor. Other risks for sustainability trade-offs and conflicts also exist, such as loss of valuable non-forest ecosystems and their associated biodiversity and ecosystem services, and competition for agricultural land.

Reforestation refers to the re-establishment of forest on land that has recently been under forest cover, while afforestation refers to the establishment of forest on non-forested land or land that has been without forests for a long time. These forests can be established through natural regeneration, plantation, or direct seeding; and they can have different purposes, such as timber and pulp production or ensuring the provision of a high quality and quantity of water to an urban area (Zhang et al. 2020). Forest restoration can accelerate the recovery of degraded forests, with special focus on reinstating ecological processes, recovering the forest structure, and restoring the biodiversity typical of climax forests (Elliott, Blakesley, and Hardwick 2013). However, the mitigation benefits of forest restoration depend on the initial level of degradation as well as the applied restoration methods (Mackey et al. 2020).

Reforestation, afforestation, and forest restoration can mitigate climate change directly through increased carbon sequestration (Lal et al. 2018), and indirectly through increasing evapotranspiration, which reduces local air temperatures (Zhang et al. 2020) and drives moisture recycling that results in rainfall generation benefits (Meier et al. 2021). Carbon is accumulated in plant biomass (i.e., aboveground biomass, below-ground biomass, deadwood, and litter), and as soil organic carbon (Bárcena et al. 2014; Paul et al. 2002). All three of the above-mentioned measures should complement, not substitute, measures to reduce deforestation and prevent forest degradation (Di Sacco et al. 2021), since the carbon stocks, biodiversity, and other ecosystem services provided by old-growth forests cannot be provided by newly planted forests within relevant societal and climate change timescales. In addition, preventing deforestation in the tropics is generally highly cost-effective compared to reforestation (7.2–9.6 times as much potential low-cost abatement as reforestation), although tropical reforestation can be more cost-effective in some countries, particularly in Africa (Busch et al. 2019). Also, (assisted) natural regeneration approaches are more cost-effective than planting (Crouzeilles et al. 2020).

The tropics have the largest forestation potential considering high economic effectiveness, fast growth rates of trees, and synergies with biodiversity targets (Doelman et al. 2020; Strassburg et al. 2020). Overall, tropical afforestation has been found to reduce warming three times more effectively than in the boreal and northern temperate regions (Arora and Montenegro 2011). In contrast to temperate and boreal regions, albedo-induced warming is of less concern in the tropics. At higher latitudes, the effectiveness of afforestation is also hampered by a slower growth rate and darker tree cover for forests than for lower-growing vegetation (Zhao and Jackson 2014), which can cause substantial surface warming, cancelling the potential carbon sequestration benefits (Arora and Montenegro 2011; Betts 2000; Schaeffer et al. 2006; Sonntag et al. 2016).

Hotspot areas for forest restoration are found primarily in Brazil, Colombia, India, Indonesia, and Madagascar (Brancalion et al. 2019). Hotspot regions for afforestation (as well as reforestation) include China, South America, sub-Saharan Africa, and the United States of America (USA), with South America and sub-Saharan Africa being responsible for at least 50 per cent of the climate change mitigation potential from afforestation (Doelman et al. 2020). A recent controversial study estimates that globally up to 0.9 billion hectares (ha) of land are available for tree canopy cover, representing a total carbon storage potential of up to 205 gigatons of carbon (GtC) (range: 133–276 GtC) over decadal timescales (Bastin et al. 2019). The potential would be higher if forestation enhancement of the water cycle is considered, but the actual land areas that can be considered for forestation are substantially lower if social, legal, ethical, and political factors are accounted for (Arora and Montenegro 2011; Betts 2000; Grainger et al. 2019; Lewis et al. 2019; Schaeffer et al. 2006; Skidmore et al. 2019; Veldman et al. 2019). Increased droughts and wildfires occurring as a result of severe climate change (RCP8.5[1]) may considerably decrease the potential canopy cover (by 0.223 billion ha and 46 GtC by 2050), particularly in the tropics (Bastin et al. 2019).

The realised mitigation effect from reforestation measures can also depend on the vegetation type replaced. Tree planting on croplands can increase net carbon storage (Bernal, Murray, and Pearson 2018; Lamb 2018), whereas afforestation on native grassland and peat soils tends to reduce soil carbon stocks, increase wildfire risk, and potentially negate net carbon benefits (Sloan et al. 2018; Veldman et al. 2017; Wilkinson et al. 2018) (also see Chapter 5). Further, forestation and tree planting should not be considered as a silver bullet solution to climate and biodiversity crises without taking bold steps to reduce GHG emissions (Holl and Brancalion 2020) and without considering the social and environmental justice dimensions, where over 294 million people in the global South live on land considered suitable for tropical forest restoration (Elias et al. 2022; Erbaugh et al. 2020; Fleischman et al. 2022).

Sustainable forest management

This has the potential to mitigate 0.4–2.1 $GtCO_2$-e per year (IPCC 2019). Forest management measures such as selection of tree species, fertilization, thinning, irrigation, or prescribed burning (Laclau et al. 2005; Ontl et al. 2019; Stape et al. 2010) can be critical for increasing carbon uptake and ensuring win-wins for both preventive and active forest mitigation measures. On the other hand, unsustainable forest management risks causing land degradation, reducing carbon stocks of forest land, and increasing GHG emissions, which can also lead to negative impacts on water quantity, quality, and flows.

Managing forests to preserve and enhance carbon stocks in biomass and soil can have immediate climate benefits but the stored carbon is vulnerable to increased temperatures and drought (Bastin et al. 2019; Seidl et al. 2017). The effectiveness of forest management mitigation measures is highly site specific and depends on local knowledge to make informed decisions on species selection and planting or harvesting strategies, for example. Harvesting natural old-growth forests that have not previously been logged inevitably leads to increased emissions. On deforested land, however, reforestation interventions leading to sustainable forestry can increase both carbon storage and biodiversity.

The temporal aspects relating to forest management initiatives are of great importance for the balance between enhancing carbon storage and meeting the demand for wood products and bioenergy. Forest carbon sinks are affected by the length of rotation and logging intensity (Lundmark et al. 2018; Mackey et al. 2020), where longer rotation times, continuous forest cover, and reduced harvesting have positive effects on the amount of stored carbon (Bartlett et al. 2020). Wood products are often presented as substitution solutions to reduce dependency on products with high negative impact on climate change, such as fossil-fuel-based materials and energy. The trade-off between maximizing forest carbon stocks and maximizing substitution depends on many factors, including the state of the managed

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[1] RCP8.5 is a pathway where GHG emissions continue to grow unmitigated, leading to a best estimate global average temperature rise of 4.3°C by 2100.

forest, regrowth rates, and estimated emissions from the product or energy source that is substituted. In a long-term perspective, sustainable forestry can be part of increasing carbon uptake and slowing down global warming, while also providing timber, fibres, and bioenergy (Högberg et al. 2021).

Sustainable forest management is a globally recognized concept that can have multiple objectives, including enhanced water quantity, quality, and flows; timber production; biodiversity; and carbon sequestration and storage. Within sustainable forest management, efforts are focused on society's various needs, including water security. It can be defined as “the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality, and their potential to fulfil, now and in the future, relevant ecological, economic, and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems” (Mackey et al. 2020). Sustainable forest management that enhances forest growth and reduces wildfire risk can lead to increased carbon sequestration and storage in forest soils (Mayer et al. 2020). In recent decades, soil carbon stocks in boreal and temperate forest areas have increased slightly (by around 6 per cent) following forest area expansion due to reforestation of agricultural land and reduced harvesting in young secondary forests, while soil carbon stocks in tropical forests have declined slightly (by around 7.5 per cent) due to deforestation (Scharlemann et al. 2014). However, the mitigation potential achieved by protecting and enhancing forest soil carbon stocks is quite small (9 per cent) compared to, for example, soil carbon stored in grasslands and agriculture (47 per cent) (Bossio et al. 2020).

6.2.2 Mitigation potential in natural grasslands, pastures, and croplands

Humans have been growing crops and herding livestock for almost 10,000 years and estimates show that altogether the derived land use changes have reduced global soil carbon by 116 Gt (Sanderman, Hengl, and Fiske 2017). Anthropogenic land use has major impacts on the carbon source or sink function of ecosystems, and degraded lands cause increased GHG emissions, with potential feedback effects on the global climate system. In addition, combinations of global change drivers such as elevated atmospheric CO_2 concentration, warming, fertilization, grazing, and land-use change influence the carbon sequestration of natural grasslands, pastures,

Sunrise over forested peaks of western Thailand. Source: Shutterstock.

and croplands. The water cycle is of high importance for carbon sequestration and storage in soils, while both land use and climate change may threaten this function.

The mitigation potential of agricultural systems is estimated at 4.1 (1.7–6.7) $GtCO_2$-e per year (IPCC 2022). Important mitigation measures include improved cropland and grassland soil carbon management, agroforestry, and improved rice cultivation. In these ecosystems, the sequestration rates depend on soil depth, initial soil carbon content, and the period of management practices. A review of arable land shows that sustainable land management can increase soil carbon sequestration, especially when using novel methods such as soil amendments (e.g., compost) and shifting to perennial grain crops, which can reduce losses and increase inputs of carbon through their roots (Olsson et al. 2023). Soil carbon sequestration will be especially important as a short-term solution to mitigating climate change over the next 10 to 20 years while other more effective sequestration and low-carbon technologies become viable (Minasny et al. 2017). A shift from annual to perennial crops has the greatest potential to increase soil carbon stocks to the level accumulated by the natural vegetation that preceded agriculture.

Grassland and cropland systems are highly dependent on reliable access to freshwater and an intact water cycle. In fact, agriculture accounts for 70 per cent of freshwater use worldwide, mainly for irrigation (FAO 2017). Unsustainable land use has a profound effect on the flux and availability of freshwater, both locally in terms of green and blue water quantity and quality, and regionally in terms of changes in evapotranspiration and precipitation. For instance, groundwater pumping for irrigation often risks depleting streamflow and watershed functioning, leading to drought and reduced access to freshwater for downstream communities. In addition, agriculture is a major source of water pollution, especially from agricultural fertilizer, pesticide run-off, and discharge from livestock production (see Chapter 5).

Improved management of soils in natural grasslands, pastures, and croplands can have a positive effect on the vegetation cover, which may influence soil moisture in several ways: it can reduce the water evaporation by shading the soil and regulating soil temperature; it can decrease the magnitude of water erosion by reducing the impacts of rainfall, run-off, and flood events on the soil; and it can reduce streamflow and sediment export by intercepting run-off and promoting water infiltration.

Improved soil carbon sequestration in natural grasslands and pastures

Grasslands, including savannas with scattered trees and open-canopy grassy woodlands, cover approximately 40 per cent of the global land surface (Dixon et al. 2014). Grassland soils store high quantities of carbon and other key nutrients, and hence are important carbon sinks in the global biogeochemical cycle (Zhou et al. 2023). Most of the biomass in grasslands is found below ground, aggregated into roots (around 700–1000 g per square metre with root lengths up to more than 2 m), where most of the carbon is stored. Consequently, grassland soils hold relatively large quantities of organic carbon and store around 28–37 per cent of the global soil organic carbon pool (Lal 2004). Despite their relatively low above-ground biomass, grasslands are thus important net sinks for atmospheric carbon, collecting nearly 0.5 GtC per year (Scurlock and Hall 1998, Imer et al 2013). The fine, extended, highly branched root system of grasses stabilizes the soil surface, significantly reducing the rate of soil weathering and degradation in exposed grasslands. Grass also accumulates organic material over a long period of time, which results in more fertile and carbon-rich soils.

Restoration of grasslands has received far less attention than that of forests and there is limited understanding of the kinds of activities that should be included in large-scale restoration of grasslands (Buisson et al. 2019). However, a recent study shows that soil carbon in tropical savannas is derived mostly from grasses (Zhou et al. 2023). In grasslands with scattered trees, soil infiltration capacity increases in the vicinity of trees. In systems with an open tree cover, such as agroforestry parklands or open woodlands, it is important to consider the water balance in the area under trees, and in small and large gaps among trees (Bargués-Tobella et al. 2014). Better soil structure under trees improves infiltration capacity, thereby reducing surface run-off and eventually improving groundwater recharge.

Improved soil carbon management in croplands

Many agricultural activities contribute to emission of GHGs, including soil drainage, ploughing, removing crop residues, adding nutrients (manures and fertilizers) and burnings. The loss of soil C is accentuated by unsustainable management practices that cause soil degradation may further increase emissions amplifying processes such as erosion, compaction and salinization that can lead to a decline in soil quality.

Improving soil carbon management in croplands can have positive effects on climate mitigation, but more research is needed to present reliable data on the soil carbon storage potential and to enable estimation of the potential of this measure for mitigation. Still, measures to keep a continuous vegetation cover and thus increase the soil carbon stock require sufficient water. In agriculture, sustainable land management practices, such as reduced tillage intensity and the use of perennial crops, have the potential to both enhance water-use efficiency and preserve soil carbon stocks, while also reducing input costs (Beare et al. 1994; Li et al. 2019). Soil and water conservation practices aimed at reducing water erosion and surface run-off, mitigating the impacts of floods, and improving soil infiltrability are crucial components in successful restoration of degraded soil. Sustainable soil and land management practices, including agroforestry and conservation agriculture, can improve capacity for soil infiltration, resulting in reduced surface run-off and erosion (Bargués-Tobella et al. 2020).

Soil erosion by water is causing major reductions in the global soil carbon stock, leading to reduced soil productivity and land degradation. Measures to reduce soil erosion are key to the protection of soil organic carbon stocks, and thus serve as important tools for mitigating climate change (Amundson and Biardeau 2018). A recent study predicts that conservation agriculture can reduce global potential soil erosion rates by around 5 per cent between 2015 and 2070 (Borrelli et al. 2020; see Figure 6.5). The study also indicates a global trend where a more intense hydrological cycle due to increased temperatures may increase soil erosion.

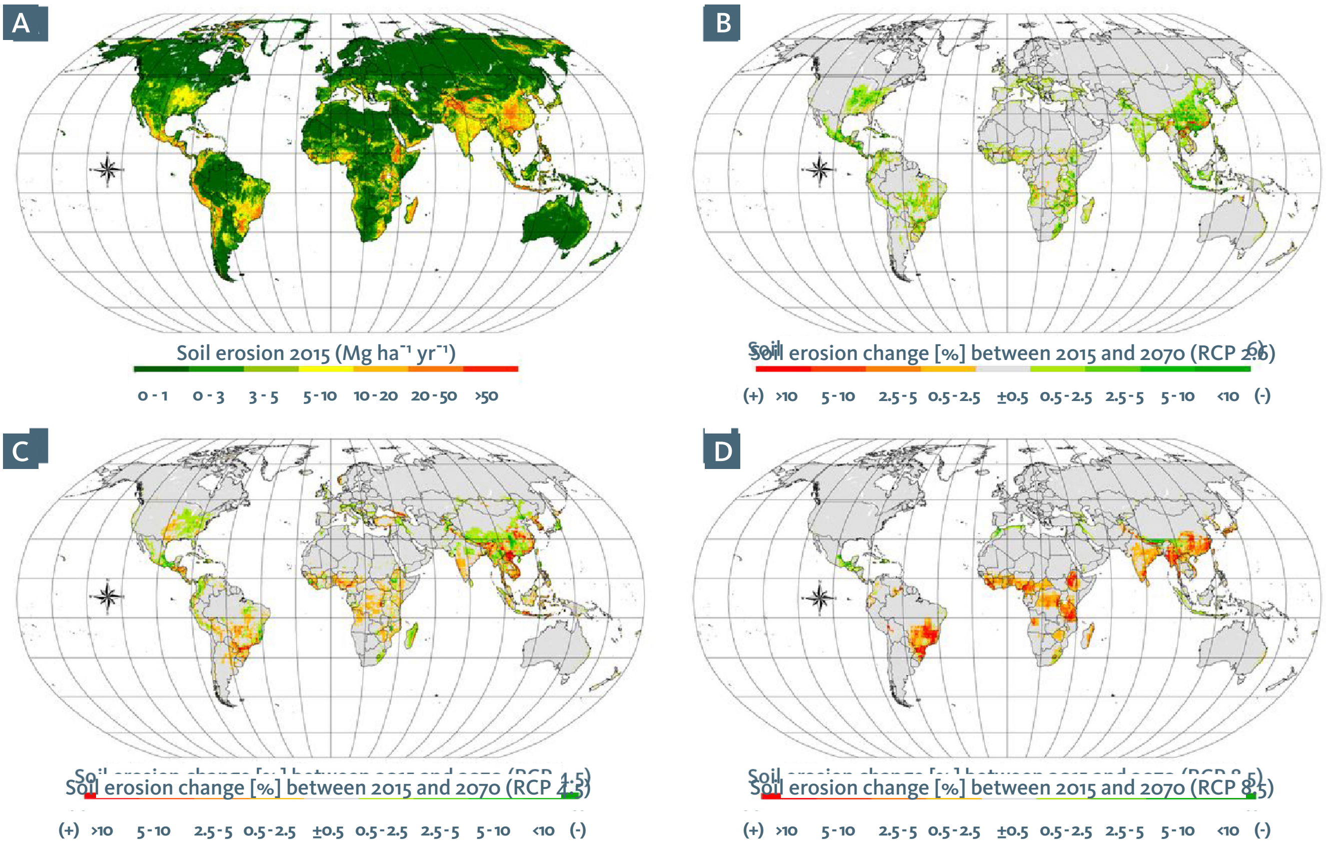

Figure 6.5. Predictions of annual average erosion rates between 2015 and 2070 by modelling change in potential global soil erosion by water using three alternative scenarios (2.6, 4.5, and 8.5) known as 'shared socioeconomic pathway and representative concentration pathway (SSP-RCP)'. The scenarios suggest different impacts on soil erosion by 2070: A. Soil erosion in 2015; B. 10 per cent soil erosion decrease by 2070 (2.6); C. 2 per cent soil erosion increase by 2070 (4.5); D. 10 per cent soil erosion increase by 2070 (8.5). Source: Borrelli et al. (2020).

Agroforestry

Trees in agricultural land positively influence the capacity of the soil to absorb, store, and release water through enhanced litter inputs and the activity of roots and soil fauna (Bargués-Tobella et al. 2020; Benegas et al. 2014). The integration of trees with agriculture can enhance the mitigation potential of a farm by increasing soil carbon sequestration and reducing GHG emissions. The adoption of agroforestry practices can therefore have strong mitigation potential while providing multiple social and ecological co-benefits (IPCC 2019), such as enhanced biodiversity, crop production, and food and nutrition security.

Agroforestry practices can transform degraded or less productive agricultural land and support the hydrological cycle by regulating the water supply, improving soil health, and reducing erosion. Restoring degraded landscapes is becoming increasingly important to mitigate climate change, and sustainable agroforestry practices have a central role to play in this development. Agroforestry offers solutions that can contribute to climate change mitigation while also promoting climate change adaptation and increased water security. Thus, agroforestry is increasingly being addressed in international policy as a sustainable land management practice to restore degraded lands and reduce erosion (IPCC 2019). As an example, forest and landscape restoration (FLR) is a long-term restoration process that has gained extensive attention internationally in recent years. Most FLR opportunities are in the form of mosaic restoration, where agroforestry plays a critical role (Laestadius et al. 2011). The main focus of FLR is to regain ecological functionality while also enhancing human well-being across deforested or degraded forest landscapes. Compared with other restoration practices included in FLR, agroforestry is particularly effective in restoring biodiversity and ecosystems while also delivering food and income security (FAO 2022).

The Great Green Wall initiative is an example of a large-scale restoration initiative that involves vast areas of cropland, rangeland, grassland, and savanna in the Sahel and Sahara region, where severe droughts occur and soil and land degradation are common. The initiative includes water and soil conservation measures to increase climate change resilience. The most common sustainable land management activities reported in the 2020 Great Green Wall status report (UNCCD 2020) were forest and watershed management. Box 6.2 summarizes the experiences and practices introduced.

Box 6.2. The Sahara and Sahel Great Green Wall initiative

The Great Green Wall initiative is a Pan-African programme launched in 2007 by the African Union. Its goal is to reverse land degradation and desertification in the Sahel and Sahara, enhance food security, and support local communities to adapt to climate change. Reducing and reversing land degradation is important for climate change mitigation as well as for achieving the Sustainable Development Goals (SDGs), including the targets relating to food and water security (SDGs 2 and 6), and life on land (SDG 15), and to balance the losses and gains of productive land to achieve land degradation neutrality (Cowie et al. 2018).

Starting with 11 core countries (Figure 6.6), the initiative has now expanded to include the drylands of North and South Africa and represents a total restoration

Figure 6.6 . The Great Green Wall initiative original 11 member countries. Source: UNCCD (2020).

potential of over 600 million ha (UNCCD, 2020). The European Union (EU), Global Environment Facility (GEF) and World Bank, among others, have provided financing for a number of implementation projects. These include the Sahel and West Africa Programme in Support of the Great Green Wall Initiative, and the Building Resilience through Innovation, Communication, and Knowledge Services project (Goffner et al. 2019; UNCCD 2020). So far, the initiative has worked with other related national and international projects to comprise an estimated total carbon sequestration potential of 138 megatons of carbon (MtC) (UNCCD 2020).

The Great Green Wall initiative has moved beyond its original conception as a wall of trees into a mosaic of sustainable land management practices to create resilient landscapes. The objective is to restore 100 million ha of land, sequester 250 million tons of carbon and create 10 million jobs by 2030 (UNCCD 2020). Communities and their preferences are at the heart of forest and landscape restoration activities and the focus is not only on trees, but also on feed, medicines, food, and fuel. Site characteristics such as rainfall regimes, land cover, soil types, and topography determine which sustainable land management measures are most appropriate for each location. For example, the most common practices in Burkina Faso, Mali, and Niger are soil and water conservation measures, sand dune stabilization, and soil fertility improvement, while in Mauritania, water harvesting and sand dune stabilization techniques are the most important (Chirwa and Larwanou, 2017).

Moreover, water is at the centre of restoration in drylands as interventions aiming to increase vegetation cover and carbon sequestration improve soil water availability, while direct water-related activities benefit vegetation greening. The role of tree cover in the hydrological cycle and its effect on groundwater and streamflow in the Sahel has been debated extensively (e.g., Ellison and Speranza 2020). Catchment studies looking at the impacts of tree cover on water yields show that forestation leads to reductions in streamflow due to higher evapotranspiration from trees, while the opposite happens with deforestation (e.g., Bosch and Hewlett 1982; Farley et al. 2005). In landscapes with scattered trees, such as the Sahel, soil infiltration capacity increases in the vicinity of trees as far as 20 m away from the closest tree stem. In an agroforestry parkland in Burkina Faso, groundwater recharge was maximized with an intermediate tree cover (Ilstedt et al. 2016). Sites treated with Zaï and half-moons (farming techniques of digging pits in less permeable soil for water harvesting) in Niger exhibited high soil water storage, promoting vegetation productivity and millet yields compared to control sites, particularly in drier years (Wildemeersch et al. 2015). Soil and water conservation practices in Burkina Faso such as stone bunds, gullies, and permeable dams have contributed to the regeneration of trees and shrubs with further carbon sequestration (Reij et al. 2009).

Overall, actions that can generate climate change benefits through carbon sequestration in soils and vegetation, while also improving the hydrology and resilience of landscapes, include the following (Berrahmouni and Sacande, 2014; Sacande and Berrahmouni, 2016).

- Promoting natural regeneration, in which farmers protect and manage the natural regeneration of native species in forests, grasslands, and croplands.
- Investing in large-scale land preparation and enrichment planting where degradation is so severe that natural vegetation will not regenerate on its own; communities select the native woody and grass species to be used.
- Fighting sand encroachment by establishing and protecting native woody and grassy vegetation adapted to sandy and arid environments.
- Mobilizing high-quality seeds and planting materials of well-adapted native species to build ecological and social resilience.
- Developing comprehensive value chains that benefit local communities and enable the flourishing of green economies and enterprises.

The most common sustainable land management techniques adopted under the initiative were forest and watershed management, terracing and soil measures, and assisted natural regeneration and reforestation (Table 6.2). Other common activities that often covered smaller areas were multipurpose gardens, nurseries, and fire and wind breaks (UNCCD 2020). Through the adoption of these measures, the initiative has so far contributed directly to the restoration of 4 million ha of degraded lands and created momentum for other national and international projects with restoration of an additional 17.8 million ha in the original core countries in the Sahel. This totals an estimated carbon sequestration potential of 138 MtC (UNCCD 2020). Value chains have been created including honey, Arabic gum, baobab, and fodder, which have also contributed to the creation of 335,000 jobs (UNCCD 2020).

Table 6.2. Great Green Wall sustainable land management practices and their benefits

	Production	**Landitation**	**Plant protection**	**Erosion control**	**Water harvesting and retention**
Forest management and agroforestry	FMNR Multi-purpose gardens Seedlings	FMNR Reforestation			FMNR Reforestation
Pasture and crop management	Intercropping Fire breaks Enclosures	Mulching Intercropping Fallow Direct seeding Contour ploughing Enclosures	Intercropping Cover crop Fallow Fire breaks Wind breaks	Cover crops Contour ploughing Wind breaks	Intercropping Contour ploughing Mulching Cover crops Wind breaks
Soil fertility management	Dune fixing Composting Terrace cultivation	Zero tillage Composting		Dune fixing Terrace cultivation	Terrace cultivation Zero tillage
Water management	Half-moon Zaï	Half-moon Zaï Rock dams Trenches		Rock dams Trenches Stone bunds	Half-moon Zaï Rock dams Contour bunds

Note: FMNR = farmer-managed natural regeneration. Source: Chirwa and Larwanou (2017); Maisharou et al. (2015).

However, progress among countries has not been uniform, with some showing more achievements than others (UNCCD 2020). Mirzabaev et al. (2021) evaluated the economic costs and benefits of land restoration under the initiative. The results show that the average annual costs of land degradation due to land use and land cover changes in the entire Sahel region during 2001–2018 were equal to USD 3 billion. About 10 years are needed for all land restoration activities to reach positive benefit-cost ratios from the social perspective. The investment needed for land restoration across the Sahel is estimated to be between USD 18 and 70 billion. To increase the speed and scale of the interventions, a renewed financial commitment took place at the One Planet Summit in January 2021 leading to a pledge of over USD 19 billion by several multilateral and bilateral organizations as well as the creation of the Green Wall Accelerator to facilitate the coordination of donors and stakeholders (UNCCD 2021).

Among the many programmes in place to support the Great Green Wall initiative, GEF is funding projects to further enhance collaboration between the various countries and stakeholders. The goal is to create an enabling environment for scaling up sustainable land management interventions and policies as well as to support the mobilization of funds, and to integrate and harmonize different scientific tools and methods and monitor interventions and their environmental and livelihood impacts in support of future investments. The project Large-scale Assessment of Land Degradation to Guide Future Investment in Sustainable Land Management in the Great Green Wall Initiative Countries takes stock of previous GEF sustainable land management projects in the four pilot countries of Burkina Faso, Ethiopia, Niger, and Senegal (Figure 6.7). The ongoing analysis of these projects will provide an indicator framework for the monitoring of socio-economic impacts (O'Byrne et al. 2022), a scaling evaluation framework to inform future investments in the region (Mechiche-Alami et al. 2022), and the identification of land degradation hotspots and an impact assessment of interventions. The goal is to maximize the environmental and socio-economic benefits of sustainable land management investments, such as carbon sequestration and regulation of water, and thereby to contribute to food and water security in the Sahel. Through a combination of partners,* including remote sensing companies, international organizations, and research institutes, this project develops science-based assessments and provides training to technical staff in the initiative's country offices.

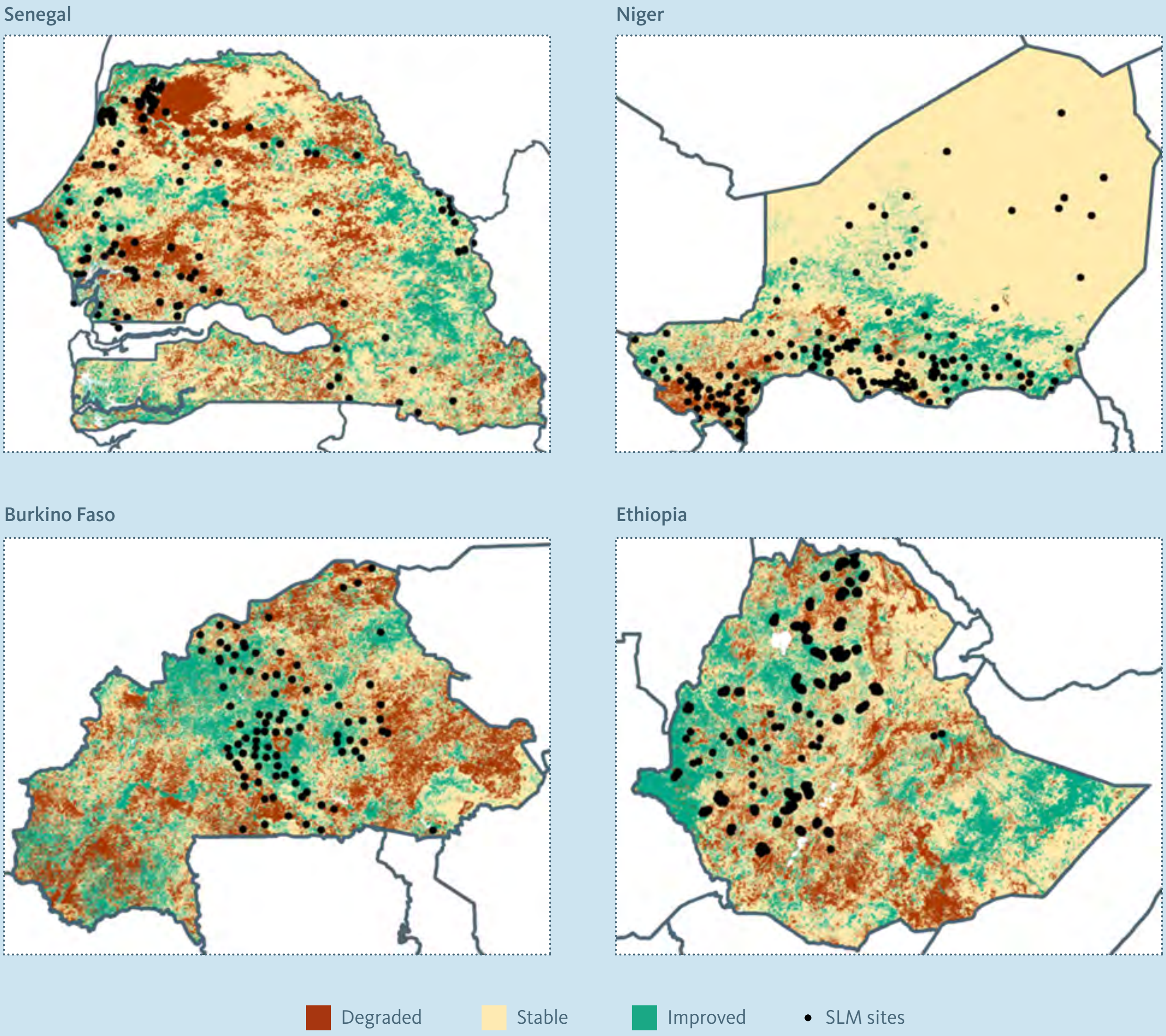

Figure 6.7. Sustainable land management intervention sites under GEF projects and assessment of land degradation between 2001 and 2018 in Burkina Faso, Ethiopia, Niger, and Senegal. Source: trends.earth (http://docs.trends.earth/en/latest/).

* The partners include Agrhymet, Danish Hydraulic Institute, European Space Agency, Lund University Centre for Sustainability Studies, National Aeronautics and Space Administration, Sahara and Sahel Observatory, Sistema, and United Nations Environment Programme.

Improved rice cultivation

Rice is a staple food for more than 50 per cent of the world's population. Rice paddies are the largest artificial type of wetland occurring globally and so constitute an important source of GHG emissions (IPCC 2022). The global mitigation potential from improved rice cultivation has been estimated to cover a range from 0.08 to 0.87 $GtCO_2$-e per year between 2020 and 2050 (IPCC 2019). 90 per cent of emissions in rice cultivation are associated with methane emissions from anaerobic conditions. When farmers adopt continuous flooding, application of nitrogen fertilizer, and use of machinery there are higher GHG emissions than with more traditional methods of production. Puddling and continuous submergence of rice fields facilitates the activity of methanogenic bacteria, thereby increasing methane emissions (Pathak et al. 2013). In contrast, the aerobic conditions of rice paddies that are periodically dry have lower methane emissions and thus may reduce global warming (Basavalingaiah et al. 2020).

The main mitigation potential in rice cultivation lies in improved management measures, i.e., considering which flooding regime to use (see Box 6.3). Continuous flooding results in much larger methane emissions than irrigating frequently during the growing season, e.g., through alternate wetting and drying (Adhya et al. 2014). In addition, compared with transplanted rice production systems, direct-seeded rice can significantly reduce GHG emissions and contribute to water saving, since less water is required for nursery preparation and puddling. The method is also less energy and labour intensive (Pathak et al. 2011). Other factors contributing to GHG emissions stem from fertilizer application and energy used for water pumping. Another important mitigation measure is to introduce improved rice varieties that are drought resistant or more suitable for rainfed cultivation (Africa has led the way in developing such cultivars).

Globally, the area under rice cultivation has grown by 11 per cent between 1990 and 2019 (FAO 2021) and now occupies more than 160 million hectares, of which Asia covers about 88 per cent (Chakraborty et al. 2017). About 90 per cent of rice is produced and consumed in Asia, but cultivation is rising in other regions including sub-Saharan Africa (Carlson et al. 2016; IPCC 2019). The demand for rice is growing, and global rice production is projected to increase by 13 per cent from 2018 to 2028, with the largest increases occurring in Africa and Asia (OECD/FAO 2019). However, some projections of GHG emissions from rice cultivation are showing a slight decline by 2030. This may be explained in diets shifting to include more protein as the average per capita income increases.

Box 6.3. Improved rice cultivation in India

In India, 85 per cent of the population relies on rice as the staple food. The area under rice has increased from 30.8 to 43.8 million ha from 1950 to 2021, with an increase in production volume from 20.6 to 122.3 million tons (Government of India, 2021). Productivity increased from 668 to 2,400 kg per ha during the same period (Dey and Dinesh 2020). The eastern part of the country, including Assam, Bihar, West Bengal, Eastern Madhya Pradesh, Eastern Uttar Pradesh, and Odisha, is an important area for rice cultivation, accounting for about 63.3 per cent of India’s total area under rice cultivation. India is a net exporter of rice, exporting about 20 per cent of the yearly produce. Iran, Iraq, Saudi Arabia, the United Arab Emirates, and Yemen are major importers of basmati rice, while Benin, Cote d'Ivoire, Nepal, Senegal, and Togo are major importers of non-basmati rice from India.

Rice production systems and the extent of methane emissions

In India, rice production systems are classified based on soil water conditions and categorized into the following four broad groups (Rao et al. 2017, Meera et al. 2014). Values for methane emissions from these production systems are presented in Table 6.3.

- **Irrigated rice ecosystems:** These are grown in bunded fields with irrigation on one or more crop rotations per year. Usually, farmers try to maintain 5–10 cm of water in the field. The wet season (June to October) is the main season for rice cultivation (Rao et al. 2008). An area of about 22 million ha is under irrigated rice systems, representing around 49.5 per cent of the total rice area.

- **Rainfed upland rice ecosystems:** The area under cultivation is about 6 million ha, accounting for 13.5 per cent of the total rice area. The monsoon season (June to September) is the main season for rice cultivation. Rice is mostly direct sown and in the dry season the fields are generally dry and bare.
- **Rainfed lowland rice ecosystems:** Here, rice is grown in bunded fields that are flooded with rainwater for at least part of the cropping season to a depth of more than 100 cm for no more than 10 days. This system accounts for 32.4 per cent of the total area under rice cultivation. Farmers have little control on water, and water depths can be shallow (up to 25 cm), medium-deep (up to 50 cm), or deep (up to 2 m). Medium- to long-duration cultivars are grown, depending on the water depth. There may be a water shortage during crop establishment and excess water during the later stages of growth. Cultivars grown should therefore have tolerance to drought in the initial stages and to submergence at later stages as well as elongation ability in semi-deep or deep water.
- **Flood-prone rice ecosystems:** These are prevalent where farmers face temporary submergence of 1–10 days or long periods of submergence of 1–5 months in depths from 50 to 400 cm or more. This system is also adopted where daily tidal fluctuations cause complete submergence (Mohanty et al. 2013). They account for about 4.6 per cent of the total rice-growing area. Yields are very low (1.5 tons per ha) and variable. June to November is the main wet/flooding season. Rice varieties are selected according to their level of tolerance to submergence.

Table 6.3. Methane emissions from different rice production systems in India (2007)

Ecosystem	Water regime	Rice area (million ha)	Methane emission (million tons)
Irrigated	Continuous flooding	6.7	1.14
	Single aeration	8.2	0.55
	Multiple aeration	9.9	0.15
Rainfed	Flood prone	3.7	0.70
	Drought prone	9.0	0.70
Deep water		1.4	0.26
Upland		4.9	0.15
Total		**43.8**	**3.65**

Source: Bhatia et al. (2013)

Reducing emissions through improved water management

Improved water management practices in rice cultivation create aerobic conditions; these control the activity of soil microorganisms resulting in a reduction in methane emissions. The choice of irrigation method affects the soil moisture and can regulate the release of GHGs. Common irrigation methods in rice cultivation include alternate wetting and drying (AWD), mid-season drainage and intermittent irrigation, intermittent flooding, and intermittent drainage, all of which may affect the soil oxidation potential. AWD can reduce methane production substantially because the time intervals between dry and wet conditions enable a shift from aerobic to anaerobic soil conditions. It can also improve water-use efficiency. These irrigation methods facilitate soil oxidation by boosting root activity and soil oxygen-bearing capacity, while minimizing the input of water that creates anaerobic conditions. Methane emissions can be reduced by 15–88 per cent (Mohanty et al. 2017). Intermittent drainage in rice, creating alternate anaerobic and aerobic conditions, is considered to be one of the best options for reducing methane emissions (Tyagi, Kumari, and Singh 2010).

Despite the benefits of AWD, its adoption has been limited, possible due to farmer apprehension that it may reduce yields (Carrijo, Lundy, and Linquist 2017). Deelstra et al. (2018) reported an increase in water productivity of 0.59 kg per cubic metre under AWD over conventional paddy rice (0.22 kg per cubic metre) because of water saving and better yields in two districts of Telangana in the Krishna River basin. Irrigation scheduling is one method that can adjust water use, time, and place of application for optimized crop production, while reducing total water use and improving the performance of irrigation systems. Scheduling irrigation with low-cost tensiometers can be a technical support to optimize irrigation in rice, resulting in water saving of about 13 per cent (Vatta et al. 2018).

Enhancing water-use efficiency, crop yields, and mitigation through micro-irrigation

Micro-irrigation can increase water-use efficiency and improve crop yields when compared with flood irrigation methods. Various micro-irrigation methods are used in rice cultivation, such as surface drip, sub-surface drip, sprinkler, and low pressurized systems. Drip irrigation (surface and subsurface) has high irrigation efficiency in rice, providing water precisely to the crop roots. It can also minimize the energy needed for pumping water. Reduction in GHG emissions were greatest for sub-surface drip systems (36–44 per cent) followed by surface drip (17–25 per cent) in rice crops. Subsurface drip systems reduced CO_2 emissions by 17–44 per cent indicating significant mitigation potential, contributing to a yield improvement of 18–31 per cent and water saving of 23 per cent compared with the conventional method (Parthasarathi et al. 2021).

Mitigation through management of groundwater irrigation

India is the largest user of groundwater in the world and agriculture is the largest user of water in the country. Out of the total 6,881 geographical groundwater assessment units, 1,186 units (17 per cent) have been categorized as ‘over-exploited’. In addition, 313 units (5 per cent) are ‘critical’, with groundwater extraction ranging between 90 and 100 per cent of recharge (Central Government Water Board, India, 2019). The number of groundwater irrigation structures increased from 6.2 million in 1986/87 to 20.5 million in 2013/14 (Mukherji 2020). Moreover, the area irrigated by groundwater has increased greatly; from 29 per cent of the total irrigated area in 1950/51 to 63 per cent in 2018, with 90 per cent of the water withdrawn used for irrigation (Jain et al. 2019). The climate mitigation options for groundwater irrigation include rationing the electricity supply, adopting micro-irrigation technologies, improving pump efficiency, improving on-farm irrigation efficiency, and managing aquifer recharge (Karimi et.al. 2012; Shah 2009).

6.3 Water dependence

As explained in the previous section, the mitigation potential of forests, natural grasslands, pastures, and croplands depends on an intact and functioning water cycle. Water is the main limiting factor for vegetation growth in many parts of the world, especially where there are periodic droughts (Knapp et al. 2002; Smith and Knapp 2001). Climate change is likely to bring more frequent and longer periods of drought, with negative effects on primary production and increased risk of biodiversity loss. Climate change presents a substantial risk to the stability of land carbon stocks and sinks (Anderegg et al. 2020) and reduced vegetation cover is therefore likely to be associated with a net loss of soil carbon and, over the long term, a positive feedback mechanism for climate change. Thus, large-scale shifts in vegetation cover can change global climatic conditions by altering the surface energy budget, leading to deterioration in local water resources (Pielke et al. 2002).

6.3.1 Mitigation measures in forests

Forest-based mitigation measures depend fundamentally on a functional water cycle. An altered water cycle can lead to droughts, floods, and reduced water quality, reducing tree growth and survival, and hence decreasing carbon sequestration. It may also threaten the very existence of a forest ecosystem, thus reducing existing forest carbon sinks. For instance, tropical forests and savannas are both possible biomes (i.e., ‘alternative stable

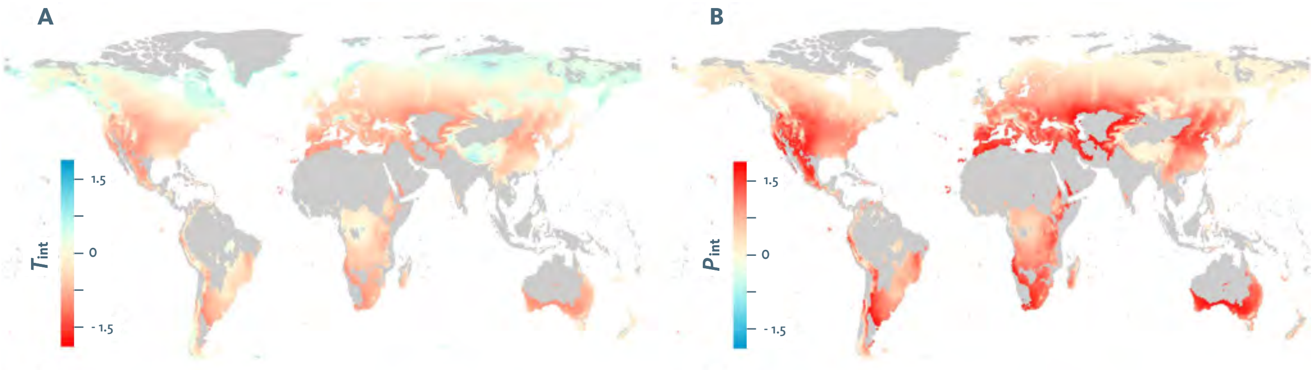

Figure. 6.8. Tree growth responses to climate changes in A. temperature and B. precipitation, based on tree-ring data sampled from 2,710 sites between 1930 and 1960. Red colours indicate strong water constraints and blue colours indicate strong energy constraints. Source: Babst et al. (2019).

states' distinguished mainly through the precipitation regime) under intermediate rainfall conditions (1000 to 2500 mm per year) in regions with mild seasonality (less than seven dry season months) (Staver, Archibald, and Levin 2011). Within this hydroclimatic envelope, the self-amplifying feedback loop of climate change involving increased aridity, droughts, and fires may induce abrupt and potentially irreversible change in a biome state (Staver, Archibald, and Levin 2011).

After sunlight and temperature, water availability is usually the most limiting factor for tree growth. Tree productivity is limited by water in many parts of the world, but to the greatest extent in the low to mid latitudes (Figure 6.8). Afforestation in arid and semi-arid regions is particularly prone to water limitations. For example, afforested areas in Mongolia have been shown to suffer from water deficit (Wang et al. 2020), while the Loess Plateau in China may need to substantially adjust the water balance in the future depending on uncertainties in climate change, precipitation change, and water demand (Feng et al. 2016; Zhang et al. 2018).

Carbon uptake in tropical forests declines considerably in dry years (Doughty et al. 2015), while drought events may cause carbon release at a level several times higher than the annual carbon sink in tropical forests (Lewis et al. 2011). However, it should be noted that in many boreal regions, water availability may already have replaced energy as the dominant limiting factor (Babst et al. 2019) and in scenarios of severe climate change (RCP8.5.), increasing temperatures and droughts could have detrimental effects on tree growth and thus carbon sequestration ability. Furthermore, drought events have a disproportionately large impact on the mortality rates of large trees (Bennett et al. 2015; Phillips et al. 2010) and, therefore, a disproportionate impact on carbon emissions and storage (Bastin et al. 2015; Corlett 2016; Fauset et al. 2015). Hence, detailed consideration of water constraints (including water demand, hydroclimatic change, planting densities, and tree species selection) is necessary to avoid overestimating the sustainable level of reforestation and afforestation for carbon sequestration.

Plantations often involve fast growing, water-intensive tree species (such as most pioneer species) that require high water availability (Cao et al. 2016; Silveira et al. 2016; Zheng et al. 2016). Irrigation is sometimes applied to increase growth rates (Laclau et al. 2005; Stape et al. 2010). Global implementation of bioenergy plantations with carbon capture and storage (as required for 1.5°C target scenarios) will require water withdrawals for irrigation of between 400 and 3,000 cubic km per year, depending on the scenario and the conversion efficiency of the carbon capture and storage process (Stenzel et al. 2019). See Chapter 7 for further information on the water implications of bioenergy.

6.3.2 Mitigation measures in natural grasslands, pastures, and croplands

As with forests, the full potential of climate mitigation in natural grasslands, pastures, and croplands can be reached only with an intact water cycle and sufficient freshwater. Measures to restore, conserve, and sustainably manage vegetation cover and soil carbon stocks depend on freshwater. If implemented correctly, these measures can, in turn, improve water flows and quality. In agriculture, sustainable land-management practices such as reduced tillage intensity and the use of perennial crops have the potential to both enhance water-use efficiency and preserve soil carbon stocks, while reducing input costs (Beare et al. 1994; Li et al. 2019).

Climate change affects not only the amount of water available, but also how it is distributed across the year. Less predictable seasonality and shorter wet seasons mean less likelihood of multiple cropping, reducing crop intensity and increasing pressure on cropland expansion. Natural grasslands, pastures, and croplands are sensitive to shifts in the local climatic regime, and climate change strongly impacts the survival and distribution of plant species, which in turn increases ecosystem vulnerability, promotes fires and soil degradation, and hampers primary production. Climate change has already strongly altered local and regional water cycles in many places, causing changes in precipitation patterns with more frequent and intense droughts and floods. These changes have impacted carbon sequestration and storage, and methane emissions in agricultural land. In some regions, climate change induced drought events have hampered crop production, while in others large floods have inundated agricultural land causing crop loss, soil erosion, pollution, and the spread of invasive species (Warner et al. 2017).

Drought and land-use change have a direct impact on the carbon source and sink function of a grassland ecosystem, which in turn has a feedback effect on the global climate system. In recent years, the increased intensity and duration of droughts has dramatically altered the structure and function of grassland ecosystems. Regional gradients in rainfall affect the distribution of major grassland types, mean root depth, and root productivity, which in turn affect soil organic carbon storage and other soil properties and processes. Grassland degradation can cause extensive soil erosion, especially during extreme events such as flooding (Lal 1995). The fine root system of grassland stabilizes topsoil and contributes to soil carbon sequestration. As a result of grassland degradation, topsoil can be washed away during heavy rain events or blown away by winds, which may also cause major problems for agriculture (Boardman and Vandaele 2010). To mitigate climate change, sustainable land use management practices, approaches, and strategies can improve grassland resilience to environmental impacts such as droughts and wildfires and regulate the carbon storage capacity of grassland soils. Box 6.4 explains different concepts to estimate water demand in agriculture, which may be useful when assessing the role of freshwater in climate mitigation in natural grasslands, pastures, and croplands.

Potato crops decimated from drought. Source: Shutterstock.

Box 6.4. Crop production, virtual water, and water footprints

As noted earlier in the chapter, crop production is a water-intensive activity, with 70 per cent of all water used globally applied in agriculture (FAO 2017). To obtain a more accurate representation of water use in agricultural production, Tony Allan developed the concept of 'virtual water' (Allan 1999; 2011), which includes all water used during the production process, thus becoming 'embodied' in the product.

Through trade in agricultural commodities, virtual water flows through an intricate global web. Many scholars have explored how these virtual water flows can be understood to improve global water-use efficiency in agricultural production, and ease environmental constraints by utilizing the best suited production sites (e.g. Hoekstra 2003; Hoekstra and Hung 2005; Yang et al. 2006). Based on this logic, Allan argued that water-scarce nations should import the most water-intensive food products as a means to alleviate national water scarcity. Following such thinking could, in theory, reduce the amount of water needed for global agricultural production, and save water on a global scale (Seekell et al. 2011; Yang et al. 2006).

The concept of 'water footprints' has evolved from discussions around virtual water. Coined in the early 2000s by Arjen Hoekstra (Hoekstra 2003; Hoekstra and Hung 2005), the water footprint of a particular good can be defined as its cumulative virtual water content. The concept has been picked up primarily by businesses seeking to assess the water going into their different products and to set quantitative targets to improve water-use efficiency per unit of product (Rudebeck 2019).

As an example of the application of this concept, the water footprint has been used at catchment scale in the semi-arid tropics in Kenya (Van der Laan et al. 2021). The assessment covered two agricultural products (maize and roses). The water footprint for maize was estimated to be 6.6 times higher than for roses. It was concluded that a water footprint assessment may help the various water users to better appreciate the finite amount of produce that can be produced in a season from a shared resource, including trade-offs.

While these concepts are appealing, there are issues with relying too heavily on water footprint assessments to determine the typical or average amount of water in a product, and its subsequent water impact. Firstly, the assessment often does not account for whether the crop is irrigated or rainfed (i.e., blue or green water). Secondly, the same crop may require different quantities of water depending on where it is grown, so the actual footprint can vary considerably depending on the climate and management conditions. Finally, if the crop is grown in a water-abundant area, a large water footprint does not necessarily imply a negative societal or environmental impact. To use water footprints as a benchmark to influence water management practices in agriculture can therefore be problematic if details are not provided.

6.4 Water impacts

6.4.1 Mitigation measures in forests

Cross-continental impacts

Over time, the effects of afforestation and reforestation on the hydroclimate can be complex due to interactions with climate change and other types of land-use change (Teuling et al. 2019). In comparison with grasslands, croplands, and other short vegetation types, the relatively high evapotranspiration rates of forests (particularly during dry periods) means they have greater potential to generate the ecosystem service of providing moisture for downwind rainfall (Keys, Wang-Erlandsson, and Gordon 2016). In areas where a large share of water evaporation is returned as precipitation over land, protecting forests may also mean protecting downwind rainfall (Figure 6.9). Current levels of human deforestation have resulted in lower rates of precipitation when compared with a scenario of pristine vegetation (Wang-Erlandsson et al. 2018). Large-scale tropical deforestation may modify circulation patterns and affect rainfall, notably in the mid-latitudes (Lawrence and Vandecar 2015). In both the Amazon and Congo

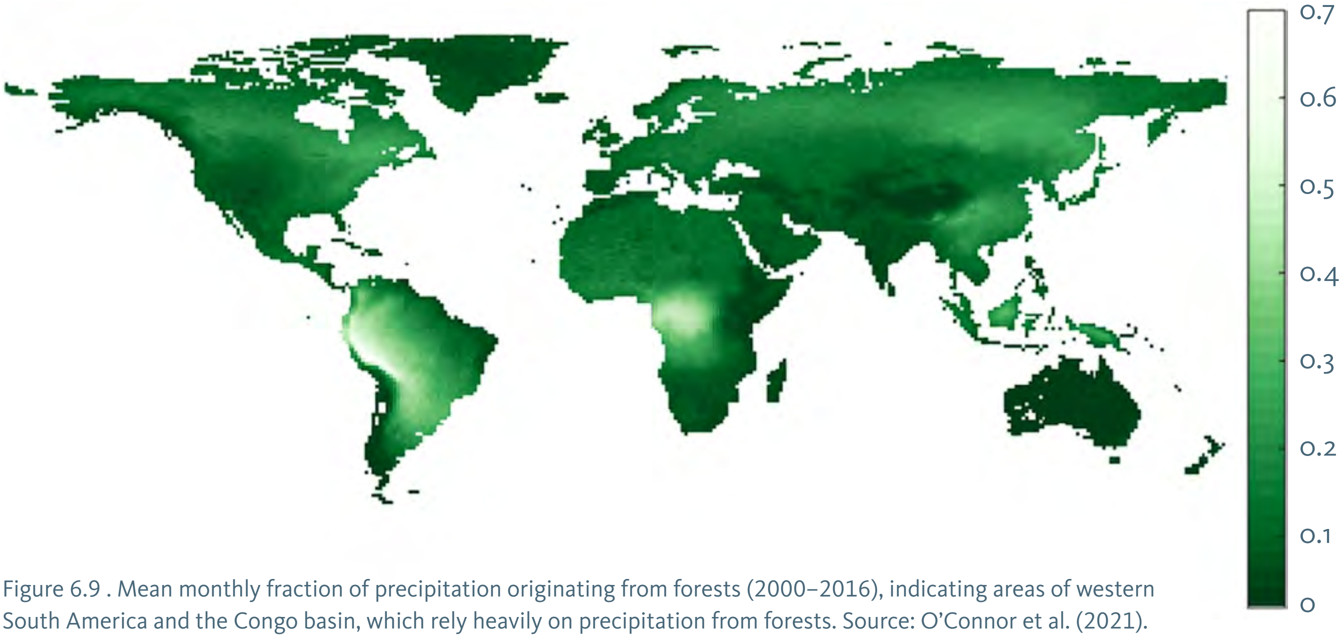

Figure 6.9 . Mean monthly fraction of precipitation originating from forests (2000–2016), indicating areas of western South America and the Congo basin, which rely heavily on precipitation from forests. Source: O'Connor et al. (2021).

rainforests, a substantial portion of rainfall is generated by evapotranspiration from the forests themselves. While interception acts as a multiplier of rainfall in the forest water cycle during wet periods, forest transpiration is particularly important for rainfall during dry periods and for buffering against droughts (Wang-Erlandsson et al. 2014; van der Ent et al. 2014; Staal et al. 2018). This recycling of forest moisture means that deforestation-induced reductions in rainfall may lead to cascading and self-amplifying forest loss in downwind regions (Zemp et al. 2017), as well as having an adverse impact on crop yields and ecosystems downwind of the rainforests (such as in the Brazilian Cerrado biome and the La Plata region in Argentina) (Oliveira et al. 2013). Prevention of deforestation in regions that contribute most to downwind forest resilience may, thus, imply multiplied carbon mitigation benefits by maintaining the rainfall needed to support healthy carbon sequestering ecosystems.

Local to regional impacts

The impacts of afforestation, reforestation, and forest restoration on local water yields are complex and context specific (Ellison et al. 2017; Ilstedt et al. 2007). Forests have higher evapotranspiration than shorter vegetation types such as grasslands and shrublands (Zhang, Dawes, and Walker 2001). Trees and forests can improve the hydrological functioning of degraded soils, particularly through enhanced soil infiltration capacity and preferential flow (Bargués-Tobella et al. 2014; 2020; Benegas et al. 2014; Bonnesoeur et al. 2019; Filoso et al. 2017; Ilstedt et al. 2007; Leite et al. 2018; Lozano-Baez et al. 2019). Hence, afforestation and tree-based restoration of degraded lands may have a less negative impact on groundwater recharge and dry season flows than predicted by most of the available scientific evidence (Krishnaswamy et al. 2013; Ogden et al. 2013; Zhou et al. 2010), in particular under intermediate degrees of tree cover (Ilstedt et al. 2016) as may be the case in agroforestry and other tree-based mosaic restoration approaches that promote an open tree cover. Moreover, in regions prone to flooding and erosion, afforestation or reforestation from short vegetation types may help reduce such risks (Lee et al. 2018; Salvati and Carlucci 2014; Wang et al. 2016). Finally, cloud forest restoration and reforestation in locations exposed to moist winds and frequent cloud cover can have positive effects on water yields by increasing cloud-water interception (Bruijnzeel and Bruijnzeel 2001; Bruijnzeel, Mulligan, and Scatena 2011; Ghazoul and Sheil 2010).

Tree planting, such as in forest restoration, afforestation, reforestation, and agroforestry, can have large impacts on the regional water cycle. Species with a high demand for freshwater risk having negative impacts on river flows, particularly in dry areas and during dry periods (McVicar et al. 2007; Mu et al. 2007; Wang et al. 2020). For instance, a study examining potential improvements in water provision by analysing changes in annual streamflow in forest restoration and other forms of forest cover expansion showed an 80 per cent decrease, as well as an increase in 6 per cent of the cases (Filoso et al. 2017). The use of longer rotation periods and species selection, by promoting tree species that consume less water and/or are more effective at improving soil hydrological functioning for instance, can also be effective in reducing the observed negative impacts of afforestation on streamflow (Ferraz, Lima, and Rodrigues 2013; Scott and Prinsloo 2008). Further improvements in water yields may be achieved through such other ecohydrological-based forest management practices as thinning or pruning, which can also increase the adaptation and resilience of forests to climate change and reduce the risk of fire (Ameztegui et al. 2017; Bayala 2002; del Campo et al. 2017; Jackson, Wallace, and Ong 2000). Anthropogenic activities in forests, such as excessive livestock grazing or litter collection, can lead to soil degradation and override the positive effects of trees on soil infiltration capacity (Ghimire et al. 2013; Ghimire et al. 2014; Lulandala et al. 2022). Hence, controlling and minimizing the impact of these activities, through grazing exclosures for instance, should be a priority.

6.4.2 Mitigation measures in natural grasslands, pastures, and croplands

The water and carbon cycles of an ecosystem are strongly interlinked, for example through the role of above- and below-ground biomass in carbon cycling. Mitigation measures in natural grasslands, pastures, and croplands generally aim to improve vegetation cover and thus have a positive influence on soil moisture. Vegetation cover can reduce water evaporation by shading the soil and regulating soil temperature; reduce the magnitude of water erosion by diminishing the impacts of rainfall, run-off, and flood events; and reduce streamflow and sediment export by intercepting run-off and improving water infiltration. For instance, the trees in agroforestry systems can influence the capacity of the soil to capture, store, and release water, as organic matter from trees enhances soil water-holding capacity and improves soil structure and porosity (Benegas et al. 2015).

In some cases, misguided implementation of climate mitigation measures in natural grasslands, pastures, and croplands may disrupt water flows and reduce freshwater availability, thus risk causing local water shortage, biodiversity loss, and harm to local communities. As an example, in grasslands and savannas throughout the tropics, carbon mitigation programmes often promote fire suppression and forest expansion, although these can have negative effects on biodiversity and ecosystem services (Abreu et al. 2017; Veldman et al. 2015).

There are large areas of agricultural land under irrigation across the globe. Irrigation can be a promising practice to promote vegetation growth which can increase the storage of soil organic carbon (SOC) and thus may have positive effects on climate mitigation. The effect of irrigation agriculture on SOC depends on different factors, such as climatic zone, soil type, agricultural management practices, soil depth and type of crops, as well as water quality (Antón et al. 2022; Tiefenbacher et al. 2021; Emde et al. 2021; Eshel, Fine & Singer, 2007). In one review study, the greatest increase in SOC (14.8%) was observed at a soil depth of 0–10 cm on irrigated semi-arid sites (Emde et al. 2021).

As in forest systems, species selection is an important part of climate mitigation measures in croplands and grazing lands, especially in arid and semi-arid regions. Species that are sensitive to water stress or have high demand for water should be grown only in areas that do not experience water stress and periods of drought. In situations where water-demanding species are needed, sustainable management options can reduce water scarcity risk. Agroforestry and other climate-smart integrated farming systems include shade crops, crop rotations, cover crops, and integrated crop-livestock or crop-livestock-forestry systems (Kakamoukas et al. 2021; Niggli et al. 2009). Technical measures to improve water-use efficiency include micro- or drip irrigation (Parthasarathi et al. 2021).

6.5 Co-benefits and trade-offs

The previous sections explain how land-based measures to mitigate climate change (i.e., protection, restoration, and sustainable management of terrestrial ecosystems) affect the water cycle. Often, this impact can be identified as either co-benefits or trade-offs. In addition, land-based mitigation measures have co-benefits for climate adaptation and resilience as well as for improving other ecosystem services such as biodiversity, plant productivity, and soil health. For all these additional co-benefits, freshwater availability and a reliable hydrological cycle are fundamental and thus there may be multiple synergies between climate action, water security, and ecosystem processes and services (Boltz et al. 2019). One example of key importance for regulating the Earth's energy, water, carbon, and nutrient cycle dynamics is to halt deforestation and ecosystem degradation to reduce GHG emissions and help preserve water cycle dynamics. Another is how the mitigation potential of land-based measures, including many nature-based solutions, is highly dependent on their ability to adapt to increased global warming, and land-based adaptation potential is strongly interlinked with freshwater availability and a reliable hydrological cycle. There is evidence that hydrological changes are already pushing some ecosystems and ecological processes towards irreversible change, such as retreating glaciers or tropical forests converting to savanna. The multiple co-benefits provided by terrestrial ecosystems in addition to carbon sequestration can offer synergies for human well-being, ecosystem health, and climate resilience; with examples including flood and other disaster risk reduction, biodiversity recovery, agricultural production, sustainable livelihoods, and water quality improvement (Raymond et al. 2017; UN Water 2018).

Although multiple co-benefits are generally provided by land-based mitigation measures, there may be trade-offs to be considered. Land degradation is a major contributing factor to climate change and, at the same time, some drivers of degradation, such as soil erosion, increased risk of forest fires, and increased expansion of invasive species, will be exacerbated by climate change (Kotiaho et al. 2018). When implementing ecosystem protection and sustainable management practices, land managers are often faced with challenging trade-offs due to constraints in tackling the drivers of degradation, such as increasing demand for agricultural land, urbanization, aquaculture, and coastal development (Epple et al. 2016). These drivers of degradation must be addressed since they may pose limitations to ecosystem protection in climate and development planning. These challenges can be overcome, for instance by strengthening monitoring, ensuring reliable data evaluation, and establishing sustainable land management systems.

6.5.1 Human well-being and social development goals

Addressing questions of how, where, and why climate mitigation measures are implemented must consider the broader political economy and place people at the centre of proposed solutions. The choice of mitigation measures often reflects the different political interests and ideas underlying development and the forest sector (Brockhaus et al. 2021; Di Gregorio et al. 2017), resulting in policy measures to reduce deforestation and degradation disproportionately targeting smallholders and shifting cultivation over political priority for large-scale industrial development (Skutsch and Turnhout 2020; also see Ingalls and Dwyer 2016 for a case in Laos and Ravikumar et al. 2017 for Peru). A failure to examine the underlying narratives and rationale behind the policy measures and their implications for local equity (Delabre et al. 2020) risks neglecting potential (and politically invisible) trade-offs, missing opportunities for potential synergies and ultimately jeopardising the sustainability of the mitigation measure of choice and resilience of the landscape of interest.

In the context of forests, trade-offs and synergies are conceptualized typically as balancing biodiversity conservation with human well-being or broader development objectives. As such, many recent conservation or mitigation interventions have been designed with a view to reducing ecosystem degradation (or enhancing forest cover) and simultaneously enhancing local human well-being – so called win-win approaches (Reed et al. 2016). However, as forest-based mitigation measures are implemented at a large scale, there will be a more plausible range of outcomes beyond a change in emissions output (Bustamante et al. 2014) and this inevitably affects a vast range of interested stakeholders. Experiences gained over the last few decades have indeed shown that win-win outcomes are the exception rather than the norm (McShane et al. 2011; Muradian et al. 2013; Sunderland et al. 2008) and interventions typically result in trade-offs and may incur unintended negative outcomes. Indeed, even initiatives that have been touted as win-wins have been revealed upon closer analysis to generate negative impacts. In addition, a systematic review concludes that tree plantations, often lauded as a win-win approach to livelihoods and mitigation, have had predominantly negative impacts on land (rights and access), livelihoods, and other intertwined social issues globally (Malkamäki et al. 2018).

It is important to note that the effects of mitigation measures are site specific and therefore it is challenging to generalize the types of trade-offs to expect or synergies to optimize. However, in designing such initiatives it can be useful to characterize potential outcomes across the institutional, socio-economic, and environmental dimensions (Bustamante et al. 2014,

Seedlings for reforestation of the Atlantic Forest, in Rosario do Limeira, Brazil. Source: Shutterstock.

Reed et al. 2020), and to consider how these will impact stakeholders across various scales and over time (i.e., local, regional, national, global). A deeper examination of how such outcomes relate to or address existing issues, inequities, or social-environmental injustices will also be needed if these measures are to gain legitimacy and ownership at all scales.

Regions identified as having opportunities for reforestation and afforestation measures are not 'empty'. On the contrary, one-third of the population in the tropical global South (around 1.01 billion) lives within 8 km of land identified as having potential for forest restoration (Erbaugh et al. 2020). Depending on design, the breadth of stakeholder engagement, and the level of prioritization to local people, each mitigation measure can, and possible will, result in both trade-offs and synergies across one or more of the institutional, socio-economic, and environmental dimensions. For example, a forest landscape restoration programme could contribute to emission reductions but is also likely to affect local land tenure and/or create conflicts relating to resource use, food production, water and soil quality, local adaptive capacity, and conservation of biodiversity. The extent to which these are positive or negative impacts will depend on the contextual conditions and institutions in place (et al. 2013). Furthermore, trade-offs and synergies can occur both within and between sectors and generate further feedback loops (both site-specific and distant) over time.

There has been weak interest in working with ecosystem services in agriculture (Sanou et al. 2023). One reason could be that external inputs have been focused on boosting provisioning services, such as yields, while the costs have been placed on public goods (regulating and supporting ecosystem services) in terms of degraded and overused resources, including water and land. Regulating and supporting ecosystem services often entails temporal and spatial scales far beyond the farm unit or growing season, which makes the impact assessment more complex than that of a well-defined farm, or field decisions usually taken by individual farmers or land-use planners. Most tools to assess trade-offs between agricultural productivity and other ecosystem services address only one or a bundle of ecosystem services relating to water, biodiversity, or climate regulation, and are often designed for different types of land use and ecosystems and applicable at different scales. One way forward could be closer collaboration between practitioners, development organizations, non-governmental organizations, and scientists to foster the co-development of tools to assess trade-offs and identify sustainable strategies for closing the yield gap, increasing productivity, and balancing the ecosystem services included in the SDG framework (Sanou et al. 2023; Tenge et al. 2007). Box 6.5 describes the potential for positive forest conservation in indigenous and tribal territories.

Box 6.5. Positive forest conservation in indigenous and tribal territories

A recent study by the Food and Agriculture Organization of the United Nations (FAO and FILAC 2021), showed that in the Amazon basin, loss of forests in indigenous and tribal territories could have catastrophic consequences for the local and regional climate, resulting in a negative feedback loop that could affect regional rainfall patterns as well as local and global temperatures. These territories have been identified as potential 'other effective area-based conservation measures' provided the territories and the Indigenous Peoples and local communities that inhabit them have appropriate legal and non-legal recognition (Jonas et al. 2014). The study also shows that on average, forests in indigenous and tribal territories in Latin America and the Caribbean are much better conserved than other forests, with indigenous territories preventing deforestation equally or even better than non-indigenous protected areas. This is the result of Indigenous People's land management practices that are based on traditional knowledge of forests and the environment. As a final point, the study highlights that to ensure the conservation of forests in indigenous and tribal territories and address the continuous pressure on them, new investment and policy initiatives should include and support the strengthening of communal territorial rights, compensation for environmental services, community forest management, cultural revitalization and traditional knowledge, and territorial governance and stronger indigenous organizations.

6.6 Policy status

Forest and water issues discussed in the academic community have focused mainly on the biophysical aspects of forest-water relationships, with a clear gap in the science-policy interface (Springgay et al. 2019). In general, policies that have an impact on or are related to forest-based mitigation measures and take account of water have been developed either in the forest or the water sector without necessarily being thought of as mitigation measures as such. It is only recently, especially with the momentum created by global processes related to climate change action, that the forest, water, and climate link has started to be taken into account, or at least acknowledged, in policies (Springgay et al. 2019). This means that while there is some advancement in policies concerning forest-based mitigation measures and water, much work remains to be done.

6.6.1 Increasing attention on the links among climate change, forests and water

The forest and water relationship started gaining momentum in 2002 with the Shiga Declaration on Forests and Water, in which experts highlighted the need for a more holistic approach to policies and management of forests and water (FAO 20002). In 2007, the Warsaw Resolution 2 on Forests and Water of the Ministerial Conference on the Protection of Forests in Europe marked another milestone as signatory Parties and the European Community committed to work on four areas of concern, including forests, water, and climate change (FAO 2002). This sparked a number of global and regional events, which have continued up to the present and catalysed action and discussion on the link between climate change, forests, and water (FAO 2002; Springgay et al. 2019).

Although water shortage represents a growing problem for rainfed agriculture, there is still little integration of water issues into policy frameworks, even within the agriculture sector. Managing water resources requires coordination and policy coherence across sectors and locations, as well as effective governance to manage interdependence and trade-offs between them. Agriculture plays a central role through the landscapes it covers and the water it uses. More coherent strategies are needed across rainfed and irrigated cropland, livestock production systems, forests, and inland fisheries and aquaculture. Incentives are important and payments for environmental services, particularly within watersheds, can play a role in sustaining ecosystem functions (FAO 2020).

Globally, specific policies relating to forests and other land use as mitigation measures have been driven mostly by the United Nations Framework Convention on Climate Change (UNFCCC) processes, namely the Kyoto Protocol, the Paris Agreement, and, most recently, the Koronivia Joint Work on Agriculture. The main aim of the latter is to mainstream the unique potential of land systems to address climate change by driving transformation in agricultural systems, and addressing the synergies and trade-offs between adaptation, mitigation, and land systems productivity. Countries are responsible for implementing the agreements at the national level, for instance through the Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs). However, when it comes to mitigation measures that include the link between land systems and water, it is important to look beyond the UNFCCC agreements since other global processes have played a significant role in the advancement of policies and measures that address this link, providing additional important entry points. This section explains how policy-related measures have evolved and highlights some of the remaining gaps.

6.6.2 Governance frameworks

Global governance frameworks including land-based mitigation measures that also address water have come from various areas of work such as the implementation of the different conventions and United Nations processes. These include the United Nations Convention to Combat Desertification (strategic objectives 1 and 3 in particular), the Convention on Biological Diversity and its recently adopted Kunming-Montreal Global Biodiversity Framework (targets 2, 3, 10, and 11 are particularly relevant) and the Ramsar Convention on Wetlands (strategic plan goals 1 and 3, and target 12 in particular) to name a few. The United Nations Forum on Forests and its strategic plan includes relevant thematic areas of work under all its goals, such as the contribution of forests to climate change mitigation and adaptation, and the protective functions of forests for soil and water management. However, the current most important instrument is the Paris Agreement under the UNFCCC, which provides a framework to include, update, and/or develop land-based mitigation policies that include water as part of the NDC process. It is important to note that as frameworks have evolved, they have aimed to align their work with each other and with other global frameworks such as the SDGs (Chapter 3).

To improve the productivity and resilience of land and water resources it is crucial to aim for productive, multifunctional landscapes and good governance that considers human rights for a more equitable distribution of water (IPCC 2019). For degraded cropland and soils, SDG 15: 'Life on land' and its target 15.3: 'By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world' is of direct relevance. Land degradation

Rusting boat carcasses in the desert, once the Aral Sea, between Kazakhstan and Uzbekistan. Source: Shutterstock.

neutrality applies sustainable land management practices to maintain or enhance soil organic carbon, avoiding or reducing future land degradation, while reversing previous degradation at the same time. Farmers can implement the land degradation neutrality framework while mitigating climate change by adopting sustainable land management approaches and technologies, such as erosion control, soil organic carbon sequestration, and water conservation (Chotte et al. 2019). At the 21st Conference of the Parties to the UNFCCC (COP21), the '4 per 1000' Soils for Food Security and Climate initiative was launched with an aspiration to increase global soil organic carbon stocks by 0.4 per cent per year in compensation for the global emissions of GHG from anthropogenic sources.

With respect to the forest-land-water nexus, a study by Springgay et al. (2019) evaluated 168 NDCs (and Intended NDCs, the earlier versions) to determine the extent to which they include forest- and land-related water resources management. The results showed that 45 per cent of those evaluated referred to keywords related to the forest-land-water nexus, while 57 per cent included agricultural measures within their mitigation sections. Since that study, the NDCs have been updated and a recent study by the Stockholm International Water Institute shows encouraging results on the evolution and coverage of the NDCs (see Box 6.6; also see Boxes 3.1 and 3.2 in Chapter 3).

Box 6.6. Integration of land-based mitigation measures in NDCs

Forests

Forest-based policies and measures were included in in 65 per cent of enhanced NDCs from non-Annex 1 countries[2] and form a significant part of mitigation strategies. In addition, measures that specifically referenced nature-based solutions were found in 45 per cent of non-Annex 1 NDCs, focused mostly on the increased role of forests and mangroves, especially in terms of their mitigation potential. However, recognition of the role of water in maintaining forest ecosystems or the connection between water resources and forest management was rare in mitigation sections, even among the Parties that acknowledged the possible connections between water and climate change within their adaptation sections.

While adaptation sections contained more detail on activities or measures in relation to forests, mitigation sections often contained generic provisions grouped around six types of activities including reforestation, afforestation and plantations, forest restoration and rehabilitation, sustainable forest management or similar, legal forest protection, and reductions in the rate of deforestation and/or reducing deforestation and forest degradation (REDD) and REDD+[3] measures. Of the enhanced NDCs from non-Annex 1 countries that included forest measures within their mitigation sections, reforestation activities were cited most frequently, followed by sustainable forest management (73 per cent) and restoration/rehabilitation of forest lands (67 per cent). Measures relating to afforestation or plantations were included in 60 per cent of enhanced NDCs, while measures relating to reducing the rate of deforestation and/or REDD+ activities were found in just over 50 per cent of the NDCs that included forest measures.

The final type of measure, forest protection, was found in one-third (34 per cent) of the NDCs that included forestry measures. One or more forest mitigation measures were found in the plans of almost all sub-Saharan African countries evaluated (35 as of January 2022), while most Latin American countries (18 as of January 2022) also included forest mitigation measures.

Very few forest mitigation measures included water components specifically or recognized the role of water in maintaining forest ecosystems or the provision of water-related ecosystem services from forests. Reforestation and afforestation can have a significant impact on hydrological systems, but such connections were not raised in mitigation sections. The main exception was the limited number of NDCs that included riparian restoration or mangrove forests within their mitigation sections.

As well as forestry activities, approximately 45 per cent of the enhanced NDCs included measures to promote a shift from fuelwood or firewood to alternative energy sources and cookware technologies.

Examples of mitigation measures include:

- **Tajikistan**: Promoting nature-based solutions, forest landscape restoration, and other relevant approaches to improve forest conditions.
- **Liberia**: Establish five new protected areas to complement the existing government commitment to increase forest protected areas to 1.5 million ha, ensuring a 3 km buffer zone, by 2030. Reduce emissions by 210 Gt CO_2-e per year by accelerating the designation of forest protected areas.
- **Liberia**: Implement an awareness campaign concerning water pollution by logging companies and deploy additional environmental inspectors or agents in high-risk areas to address logging-related pollution by 2025.
- **Malawi**: Riparian restoration: Around 36,000 ha of native species and bamboo to be planted within riparian zones and wetland borders to enable higher ecological productivity and sustainable harvesting.
- **South Sudan**: Improve the efficiency of biomass use. South Sudan will focus on improving energy efficiency in the use of biomass, in particular, fuel wood and charcoal in the traditional energy sector.

Natural grasslands, pastures, and croplands

Of the 114 enhanced NDCs evaluated, 57 per cent included agricultural measures within their mitigation sections. However, specific water-related agricultural mitigation measures around croplands and rangelands were relatively uncommon, although they were often more common in adaptation sections. Instead, many enhanced NDCs included generic measures regarding climate-smart agriculture, rice production, and improvements in irrigation. In addition to these measures, other measures cited by one or more parties included soil carbon measures, industrial farming energy efficiency, enteric methane from livestock, reduction of fossil fuel inputs, sustainable land management, rainwater harvesting, and solar-powered irrigation pumping. For example, El Salvador, Malawi, and Rwanda noted connections between soil ecosystem and soil conservation measures as providing co-benefits for mitigation.

Close to 65 per cent of enhanced NDCs included mitigation measures in relation to the increased use of biofuels or biomass in their respective emissions targets. These measures were found in multiple sectors, including energy, waste, agriculture, transport, and forestry. Most of these measures were silent on the main source of biofuel or biomass for energy purposes, but all have implications for water resources irrespective of the means of generation. Such interactions were not recognized in mitigation sections, except for the enhanced NDC from Tajikistan.

Examples of mitigation measures include:

- **Albania:** Improved sustainable cropland management: Development of agroforestry is projected to be progressively increasing to 100 ha in 2030. Improvement of agricultural soil practices help storing carbon in soils in areas that increase progressively to 20 per cent of cultivated cropland in 2030. In 2030, the application of this measure allows a reduction of emissions estimated at 167 kt CO_2-e per year compared to the ‘business as usual’ scenario.
- **Liberia:** Deploy at least one solar water pump and/or spring irrigation system for crop irrigation for communal farms with land constraints in each county by 2030. Link agricultural development with the National REDD+ Strategy by 2025.
- **South Sudan**: Implement initiatives to reduce emissions related to agricultural soils. Agricultural soils are a major emitter of GHGs, contributing more than 50 per cent to total agricultural emissions (in 2015). Thus, introducing measures for reducing soil emissions will be a key aspect for South Sudan.

Source: UNDP-SIWI Water Governance Facility (2023).

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2. Parties to the UNFCCC not listed in Annex I of the convention are mostly low-income developing countries.
3. REDD+ includes additional conservation and climate change mitigation measures.

Several initiatives have been launched at the global and regional levels to catalyse action on forest- and land-based mitigation. Global initiatives include the United Nations Decade on Ecosystem Restoration (see Chapter 3) and the Bonn Challenge, a global initiative aiming to restore 150 million ha of degraded and deforested landscapes by 2020 and 350 million ha by 2030 (Dave et al. 2018). Another initiative is the New York Declaration on Forests, a political declaration endorsed by numerous actors aiming to cut forest loss in half by 2020 and strive to end it by 2030. More recently, the Glasgow Leaders' declaration on forests and land use at the UNFCCC COP26 committed world leaders to working together to halt and reverse forest loss and land degradation by 2030 and provide substantial political support to accelerate action. The declaration does not mention water specifically, but it does emphasize the role of forests in maintaining ecosystem services.

Regional initiatives play a particularly important role as they can provide an effective means for regional and transboundary cooperation with actions targeted specifically to address regional and local challenges. Relevant initiatives include the Great Green Wall for the Sahara and the Sahel initiative (see Box 6.2) as well as regional initiatives under the Bonn challenge such as the African Forest Landscape Restoration Initiative (AFR100), Initiative 20x20 in Latin America and the Caribbean, and ECCA30 (which aims to restore 30 million ha of degraded and deforested land in Europe, the Caucasus, and Central Asia).

6.6.3 Regulatory instruments

Global governance frameworks provide the basis for national and subnational processes that establish regulatory instruments. Their success depends on strong national and sub-national enabling environments and inclusive approaches across sectors. These instruments often include integrated land use or water resources management, land tenure legislation, and restrictions in use and access (i.e. protected areas). While many of these instruments may not have been developed initially for climate change mitigation specifically, they clearly address or have an impact on what we now consider as land-based climate mitigation measures.

While there have been vast improvements in the management of protected areas, other effective area-based conservation measures are increasingly being considered as an alternative. They have been recognized and encouraged under the Convention on Biological Diversity since 2010 and are defined under its Decision 14/8 as "a geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in-situ conservation of biodiversity, with associated ecosystem functions and services and, where applicable, cultural, spiritual, socio–economic, and other locally relevant values." Recognition of other effective area-based conservation measures in national legal frameworks and supporting mechanisms that, for example, limit industrial development or natural resource extractions, can prove to be an effective regulatory instrument in key areas for forest-based mitigation actions including water management, such as forest conservation and restoration.

While relevant regulatory instruments may not be framed as climate mitigation instruments per se, instruments developed under different sectors and alternatives to traditional instruments have the potential to be effective. Their success depends on the inclusion of other relevant sectors, recognition and inclusion of all relevant actors, and management that uses a landscape approach. Furthermore, regulatory instruments should be accompanied by economic and financial mechanisms and incentives (see the next section).

6.6.4 Economic and financial mechanisms

Effective climate mitigation strategies and policies should always integrate regulative and informational instruments with financial mechanisms. This section gives a brief overview of the policies and market-based instruments that can be classed as 'carrots' (e.g., rewards, incentives, payments, and blend-finance) to promote success in forest-based mitigation measures.

Most of the literature on market- and incentive-based public instruments focuses on the broad concept of payments for environmental Services (PES), which are defined as "transfers of resources between social actors, which aim to create incentives to align individual and/or collective land use decisions with the social interest in the management of natural resources" (Muradian et al. 2010). It has been demonstrated that PES allows for greater integration and cooperation between the agroforestry and water sectors as these approaches are often based on a multi-stakeholder dialogue among land managers and other resource-dependent industries (e.g., utilities, hydropower, irrigation, etc.). Furthermore, it has been suggested that PES schemes could go hand in hand with strengthening local governments and community management (FAO, IUFRO and USDA, 2021), offering win-win solutions and aligning public, private, and civil society interests around natural resource management. REDD+ is one example where forest conservation and restoration as a climate change mitigation measure is incorporated in what could be considered a PES scheme for carbon.

PES schemes may be classified depending on the role played by the public sector, which can intervene as a buyer (as in the case of agri-environment schemes in the EU and USA) and/or as a legal actor providing a framework with an obligation to offset emissions or other resource use (scope taxes, Emission Trading Scheme, etc., see Table 6.5).

Table 6.5. Funding instruments for ecosystem services generated by forest- and land-based mitigation measures

TYPE	INSTRUMENT	DESCRIPTION
Public regulated	Regulated carbon market	Carbon markets can be divided into two types: regulated compliance and voluntary (see below). The regulated market is used by companies and governments that are required by law to account and offset their GHG emissions. Regulated compliance markets have legally binding compliance standards for emission reductions, which can be implemented at international, national, and regional levels. Examples of regulated markets include UNFCCC's REDD+ mechanism and the three mechanisms of the Kyoto Protocol: the Clean Development Mechanism, the Joint Implementation and the EU Emissions Trading Scheme.
	Agri-environment schemes	These are well-known in the Australia, Europe, and USA, and can be traced back to the 1970s, before the PES concept was conceived. They are typically national/continental incentives schemes, with little targeting and additionality. However, they constitute the main type of scheme for western countries, often incentivizing tree planting, hedgerow maintenance, fire control, and sustainable forest management for water quality. Some 90 per cent of EU funding for forests comes from the European Agricultural Fund for Rural Development.
	Water-forest scope taxes	Scope taxes can be used to generate funding from natural resource exploitation. These mechanisms are based on the adoption of water charges/fees, mainly but not exclusively in the hydropower and drinking water sectors. The funding generated is often associated with an obligation to reinvest the revenues into forest and catchment restoration activities. This is the case for several water funds in Asia and Latin America that rely on water charges as a funding source for catchment and forest restoration.
Private	Voluntary carbon markets	Voluntary carbon markets emerged in the mid-1990s, are self-regulated, and exist separately from carbon markets set up by governments in response to the 1997 Kyoto Protocol. They usually work with private forest carbon certification standards (such as Gold Standard, Verified Carbon Standard, Verra carbon standards, etc.) where reforestation projects certify a certain amount of CO_2 stored by producing 'carbon credits', and carbon brokers then place these credits on the private market for CO_2 offsetting. In 2021, the voluntary carbon credit market exceeded USD 1 billion for the first time and is projected to increase 15-fold by 2030 (Forest Trends' Ecosystem Marketplace 2021).
	Voluntary certification schemes	In these schemes, producers send a signal to consumers that environmental impacts are positive (in relative terms) and consequently gain a premium on the market price. The best known are the Forest Stewardship Council (FSC, with 230 million ha certified forest area) and the Programme for the Endorsement of Forest Certification (330 million ha). Since 2018, FSC has developed a specific procedure to verify ecosystem services impacts and allow for registered sponsorship and claims. A recent Worldwide Fund for Nature report highlights the new FSC strategy on PES development (WWF 2022), which relies on short ecosystem services value chains, which build direct connections between forest managers and communities, and sponsors.
	Investment blended funds	These are private funds such as environmentally focused bonds, loans, or equity, funded by impact or philanthropic investors that support green-grey infrastructure projects to fulfil their impact-oriented missions while expecting a return on the investment generated by cost saving from reduced operational costs. These funds may also be public, such as the Land Degradation Neutrality and the European Investment Bank Natural Capital Financing Facility. These funds are often coupled with technical assistance and grants funds to deliver blended-finance programmes.

Banana and eucalyptus agroforesty plantation. Source: Shutterstock.

Where the state does not intervene, the private market may step in (with voluntary carbon and ecosystem services markets). PES markets provide funding mainly for forest mitigation relating to carbon, water, and biodiversity offsetting, which are the main ecosystem services required by the private sector. Table 6.5 summarizes the main funding mechanisms available for forest- and land-based climate mitigation measures. Various relevant financing mechanisms of the UNFCCC and other multilateral environmental agreements are addressed in Chapter 3, such as the Global Environment Facility, the Green Climate Fund, the Land Degradation Neutrality Fund and the Global Biodiversity Framework Fund.

Economic and financial mechanisms are being promoted by policymakers, scientists, and the private sector, with considerable numbers of initiatives, case studies, and best practices available for scrutiny. However, relevant, effective, and large-scale instruments based on the private market are often lacking or remain in the development stage. Nevertheless, an improving trend is clear, especially after COP26, where the Glasgow Leaders' Declaration on Forests and Land Use committed 141 countries representing 90 per cent of global forests to "significantly increase finance and strengthen financial commitments from both public and private sources". COP26 has also opened the door to carbon credits generated by the private sector to offset within the regulated market. In 2022, the European Commission released its carbon farming initiative, regulating public and private land-based carbon markets in the EU. Moreover, many private initiatives such as the Science Based Targets Network are building new market demand for water and biodiversity offsetting under the 'nature positive' concept. This will play an important part in boosting the future of these instruments, with the hope that these incentives will build on strong benefit-sharing mechanisms and ecosystem services ownership, ensuring effective positive impacts on the ground.

6.7 Potential implications for governance

Globally, recognition and implementation of land-based mitigation measures that encompass water management are moving towards more holistic and multisectoral approaches in governance frameworks, regulatory instruments, and financial mechanisms. While it is encouraging to see advancements in this direction, gaps remain, especially when it comes to national and local implementation. Closing these gaps will depend on strengthening the science-policy interface by using the most up-to-date science and considering the complex and potentially cross-scale feedback loops of land-based mitigation measures, as well as the potential trade-offs and synergies among different benefits and constraints. Systems thinking and integrated landscape management approaches can be useful in this context (Seddon et al. 2020; Farooqi et al. 2020).

Furthermore, it is important to consider the relationship between land-based mitigation measures and water management at different scales of governance. At the local and sub-national scales, policies and management plans often account for the water impacts of forest-based mitigation measures on blue water (e.g., as part of catchment management or national adaptation programmes (Pramova et al. 2012) but other aspects of water-related dependency, impact, and feedback are seldom considered (Ellison et al. 2017). For instance, proposals for integrative management and consideration of atmospheric processes are yet to be linked with policy and governance in climate mitigation contexts, and more work is needed to assess how these concepts can be integrated in existing mitigation measures such as the Clean Development Mechanism, REDD+, and NDCs.

As global governance frameworks move forward, it is also important to consider all available information and tools to improve indicators, methodologies, and monitoring to achieve global goals. For example, the process of refining the SDG indicators and their methodologies is an evolving process that needs to be reviewed periodically in accordance with the United Nations General Assembly Resolution A/RES/71/313. Also the NDCs are reviewed every five years, which provides an opportunity to build and improve on previous NDCs and to revise national policies to ensure that targets are met.

6.8 Conclusions and outlook

Land systems mitigation measures can be cost-effective and generate substantial win-wins among water, biodiversity, social, and other sustainability goals. However, depending on the context, time-scale considerations, and implementation processes, there is a substantial risk of unrealised mitigation potential and negative impacts on other water, biodiversity, social equality, and other sustainability goals (see section 6.5). As such, there is a need to ensure systems thinking in the management and governance of land systems mitigation measures that account holistically for interconnected issues relating to water constraints, land availability, carbon sequestration, biodiversity implications, local livelihoods, and regional development, for example.

Land-based climate mitigation has a high carbon emission reduction potential, which is linked intrinsically with the water cycle. Of the various mitigation measures, the prevention of deforestation, and forest and land degradation has historically received the greatest attention and investment. However, while commitment to reducing deforestation remains high on the global policy agenda, the past decade has also seen an increasing focus on forest and landscape restoration through multilateral environmental agreements and other initiatives, such as the Bonn Challenge and the United Nations Decade on Ecosystem Restoration. So far, these measures and mechanisms have been focused on carbon management. More recently, however, there has been increasing interest in co-benefits related to water and biodiversity, from both an ecological point of view and market demand in relation to current nature-positive targets.

Nevertheless, while many international agreements highlight the importance of co-benefits and natural resource-based livelihoods, mitigation measures and instruments may not consider local social-ecological dynamics adequately in these changing land systems. In most cases, such factors as risks to the regional water cycle and dependence on freshwater resources are surprisingly insufficiently analysed and quantified in the creation and negotiation of mitigation policies. Similarly, the links between changing forest systems/water cycles and adaptive livelihood strategies are poorly understood.

All land-based mitigation measures must account for the water risks and water cycle changes that are already occurring under climate change, including a reduction in regional and global agricultural productivity, irreversible damage to biodiversity, and conversion of forest carbon sinks into carbon sources. All climate mitigation measures must account for their social and environmental justice implications to local populations. Land-based mitigation measures are also integral to non-local drivers of forest-land-water systems and require consideration of the links with trade, migration, hydroclimatic teleconnections, and international frameworks, for example. This chapter shows the importance of adopting large-scale system dynamics thinking and an integrated approach to land-based mitigation to achieve the best possible climate and sustainability benefits. All financial mechanisms and public policies should support holistic approaches, avoiding to only focus on carbon and instead integrate water and biodiversity conservation as key goals and co-benefits, ensuring benefit-sharing with local communities.

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CHAPTER 7

Mitigation measures in energy systems

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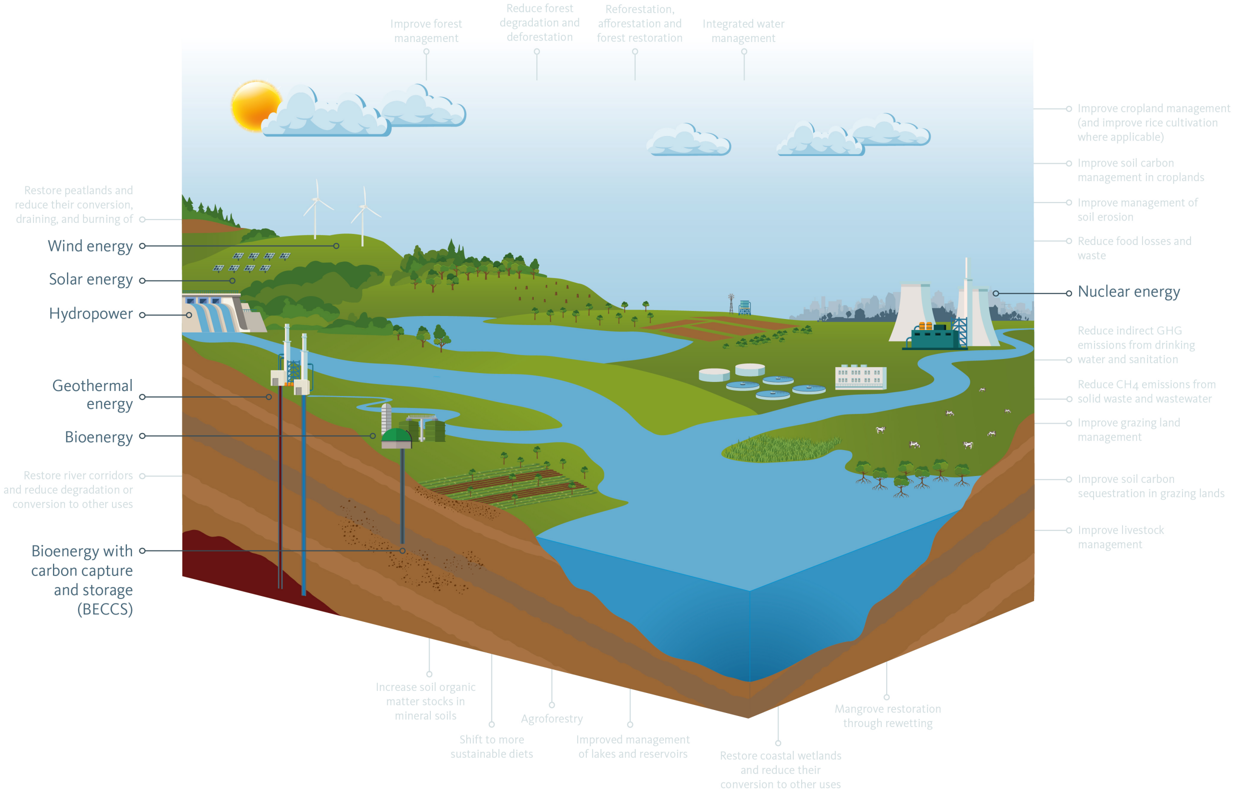

Figure 7.0. Mitigation measures in energy systems. Source: SIWI.

Highlights

- Water is a significant consideration for all energy production except possibly wind power and solar PV. Bioenergy, hydropower and thermal energy generation from solar, geothermal, and nuclear power are low-emission energy sources with substantial water requirements. The benefits provided by these options must be weighed against potential water risks and impacts on freshwater ecosystems.
- Low-emission energy transition plans must include analysis of projected demands, availability, and impacts on water as well as potential risks to water availability caused by climate change. Effective water management to buffer against the impacts of climate change is needed to protect energy infrastructure and ensure the reliable supply of electricity and energy sources.
- Transitions toward low-emission energy can reduce pressure on water, but this will depend on the future mix and management of energy sources. The transition to renewable energies can create opportunities to reduce pressure and impacts on water resources from the energy sector, due primarily to lower water demands from solar photovoltaic (PV) and wind generation compared with fossil fuels.
- As some of these transitions can potentially increase pressure on water resources, related risks must be considered in energy planning. Low-emission scenarios with high demand for negative emissions imply an increase in water consumption, particularly for bioenergy, with large ranges in potential water requirements. Low emission energy scenarios often lack quantification of impacts on water quality and ecosystems, which must be incorporated in national, local, and regional planning.
- Mitigation strategies including bioenergy must consider their potential impacts on and demand for water sources. How much, where, which type, and how to produce bioenergy are critical questions that potentially have the largest impact on the global water cycle. Sustainable water management in bioenergy with carbon capture can in certain contexts provide both energy and climate mitigation benefits.
- Expansion of solar and wind power and efficiency improvements account for meeting as much as 50 per cent of energy demand by 2050 in many scenarios to meet climate targets. If not reached, there is likely to be greater demand and pressure placed on water resources from all other alternatives. To enable this expansion, strategies are also needed to mitigate potential water risks for energy storage solutions, including pumped hydropower as well as mining for minerals such as cobalt, copper, lithium, and rare earth materials.

7.1 Introduction

Global warming cannot be limited to well below 2°C (above pre-industrial levels) without rapid and deep reductions in greenhouse gas (GHG) emissions from energy systems. The International Energy Agency (IEA 2022) estimates that 36.3 gigatonnes (Gt) of CO_2 emissions resulted from energy combustion and industrial processes in 2021, which was an increase of 6% over the previous year. This is the largest source of global emissions, accounting for nearly three quarters, coming primarily from the use of fossil fuel energy sources (IEA 2018). In 2020, about 80 per cent of total energy supply was derived from oil, coal, and natural gas (IEA 2020a). The transition to renewable, cleaner energy sources is central to all climate mitigation plans and pathways towards achievement of the Paris Agreement targets. In the IPCC (2022) modelled pathways to reach global net zero by 2050 – a majority of GHG reductions (ranging between 54 – 90 per cent) are projected to be achieved through shifts to low-emission energy supply and curbing energy demand. Despite the recent growth in renewable energy deployment and low-carbon energy technologies, emissions from the energy sector need to be reduced further. An additional 12 Gt of CO_2 emissions need to be abated by 2030 to get the world on track for reaching net zero energy emissions targets, and this needs to be accompanied by reductions of almost 90 million tons (Mt) in methane emissions from fossil

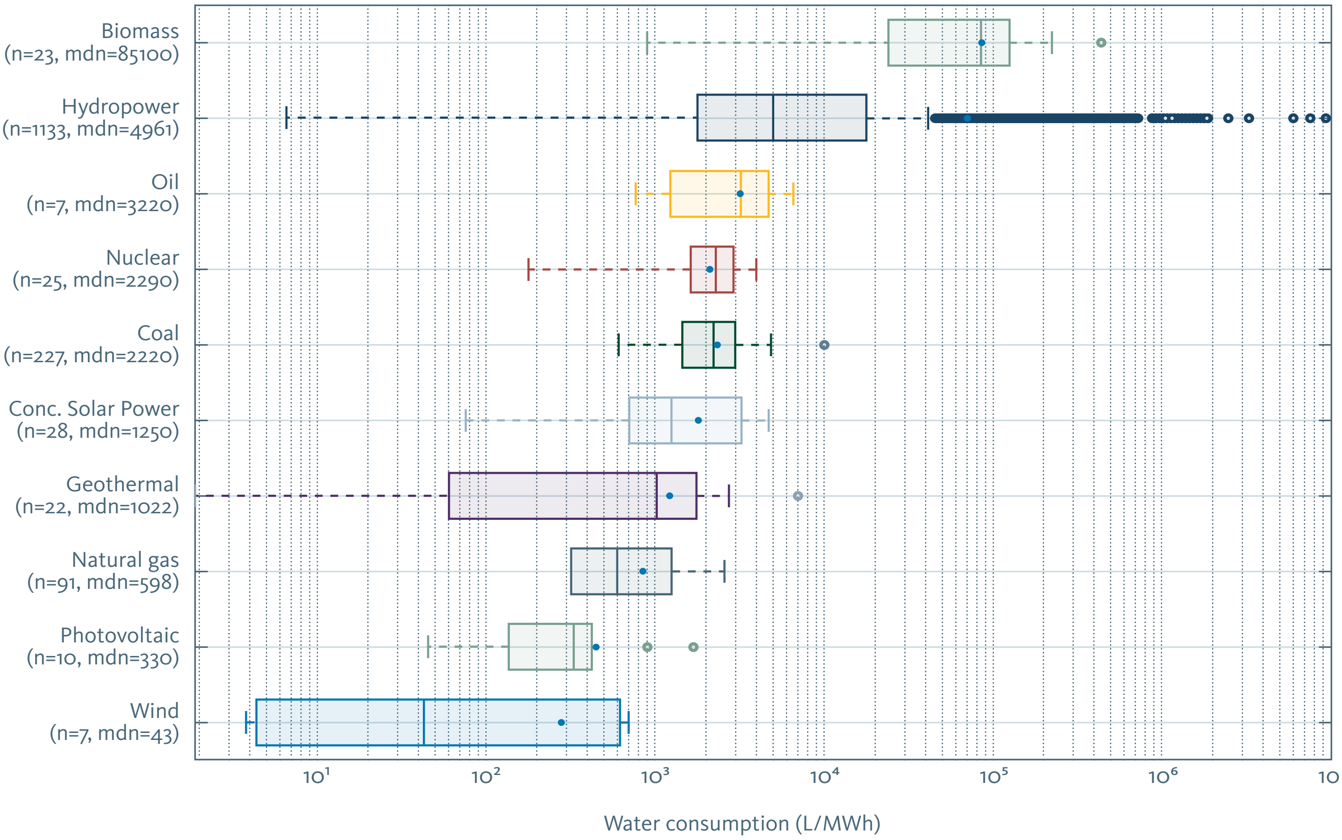

Figure 7.1. Range and median estimate of water use for electricity production by type measured in litres of water per megawatt hour of electricity produced. Source: Jin et al. (2019).

fuel operations (equivalent to another 2.7 Gt of CO_2 emissions) (IEA 2021f). This would be 25 per cent below the International Energy Agency (IEA) Sustainable Development Scenario targets in previously estimated Intergovernmental Panel on Climate Change (IPCC) pathways (Rogelj et al. 2018), and drastically divergent from current stated policies and commitments, which set a track for a slight increase in emissions to 36 Gt by 2030 (IEA 2021f).

In all energy investments, planning, and operations, the water required during the production process and the impacts of the energy production process on water resources and ecosystems need to be considered. In some parts of the energy mix, water is a central component generating, storing, or transferring such energy as hydropower and geothermal power or some hydrogen storage technologies. The requirements and impacts on water vary between energy carriers and depend on the way in which each energy carrier is being produced (Jin et al. 2019, Figure 7.1).

This chapter provides an overview of the role of freshwater in energy production of non-fossil-fuel energy sources. Each of the low-emission energy types (hydropower, bioenergy, geothermal, nuclear, solar, and wind) are presented as a mitigation measure and described in individual sections. This report reviews current uses of each energy type and projections from scenarios provided by IEA (IEA 2021f), the International Renewable Energy Agency (IRENA) (IRENA 2020), and IPCC (Rogelj et al. 2018) that are in line with limiting global warming to 1.5°C (above pre-industrial levels) and achieving net zero emissions. Under the IEA pathway to net zero emissions by 2050, the energy sources covered in this chapter will need to provide 90 per cent of electricity and 80 per cent of total energy supply, as coal and oil power plants (without carbon capture and storage [CCS]) will be phased out (IEA 2021f). The mitigation potential for each energy technology is discussed in terms of both the estimated emissions of GHG per unit of energy/electricity produced and estimates of reductions in emissions provided compared to fossil alternatives. Figure 7.2 provides a summary of estimates from IPCC (2022) showing estimated mitigation potential of each energy option assessed in this chapter. Besides quantitative estimates on water demand for each mitigation measure, this assessment covers implications for water governance and management, as well as co-benefits and trade-offs.

Many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030. Relative potentials and costs will vary across countries and in the longer term compared to 2030.

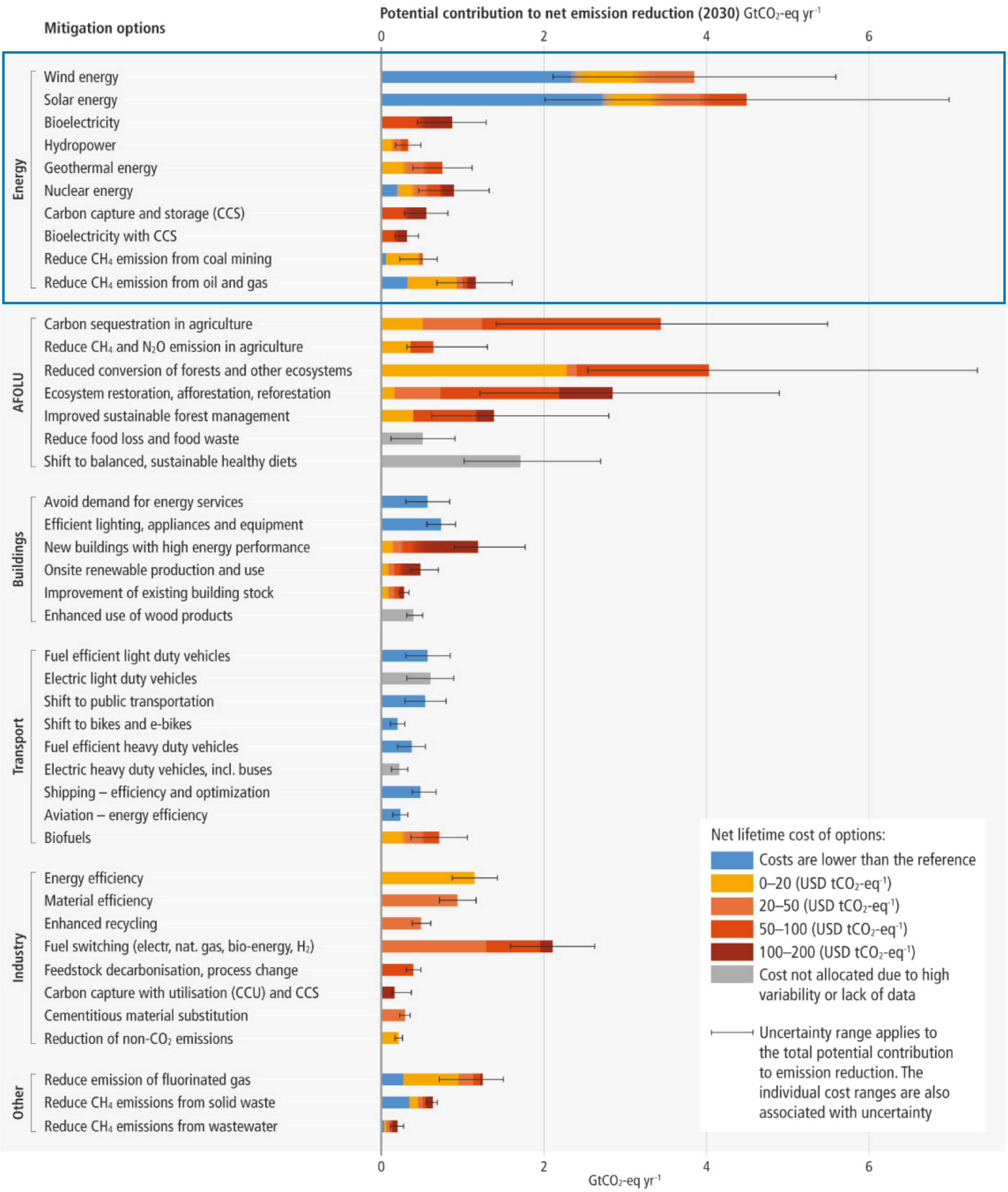

Figure 7.2. Mitigation measures within the energy sector (top box) and their mitigation potential to reduce net emissions by 2030. Source: IPCC Sixth Assessment Report, https://www.ipcc.ch/report/ar6/wg3/figures/summary-for-policymakers/figure-spm-7/.

Nuclear power is included as a mitigation measure as it is present in most scenario pathways for climate mitigation to achieve the Paris Agreement targets and has significant implications on water resources. Natural gas and coal power with CCS, however, are not classified as mitigation measures because they still have a significant emission factor (Jacobson 2020). As these energy sources remain part of most climate mitigation planning at present, the implications of CCS on mitigation and water are reviewed in brief in Box 7.1.

Measures to improve energy efficiency and reduce demand are also critical. IEA (IEA 2020a) projects that for scenarios depending upon technologies alone, half of emission reductions would depend on solutions that are not yet commercially viable. Demand management and efficiency are likewise needed to reduce overall pressure on water sources for energy production but are not covered here as specific mitigation measures. This is discussed further in Chapter 8 as a cross-cutting type of measure that also applies to water systems (Chapter 4) and land systems (Chapter 6). Green hydrogen, energy storage, and battery technologies are also discussed separately in Box 7.4, as these are critical issues and potential enablers for renewable energy transitions but are not classified as direct mitigation measures. Following a review of each energy type, the chapter concludes with an outlook of key issues to be addressed for future water, climate, and energy security.

Box 7.1. Non-renewable energy sources and water: Natural gas and coal power with CCS

In 2018, coal (38 per cent) and natural gas (23 per cent) accounted for over 60 per cent of electricity generation (IEA 2020b). These are expected to reduce to less than half of total electricity production in 2022, showing progress in the acceleration of renewable sources on the market (IEA 2021c). Coal power generation requires large volumes of water, primarily for cooling in thermal plants. Natural gas, while emitting somewhat less CO_2 than oil and coal, has a much higher emissions factor than renewable alternatives. Moreover, leakages from natural gas plants have been found to directly emit large quantities of methane, a very potent GHG, posing great climate risks (Alvarez et al. 2018). Natural gas abstraction produces large volumes of contaminated water. Hydraulic fracturing, which involves pumping liquids at high pressure to fracture rock surfaces to release natural gas, is both water intensive and poses risks for contamination of hazardous chemicals if generated wastewater is not properly treated and disposed of. Natural gas is also used in thermal electric power plants, which can also withdraw and consume significant volumes of water. As is the case for all thermal electric plants, the requirement for water, both withdrawn and consumed, depends on the type of turbine and cooling system used (see Box 7.5).

The addition of carbon capture processes to coal and natural gas power generation is likely to be part of the energy transition and will lower emissions. IPCC notes that increasing CCS for fossil and biomass carbon is a common key characteristic in most assessed energy pathways to reach the 1.5°C target (Rogelj et al. 2018). Rosa et al. (2021) estimated that the water footprint of CCS can range from roughly 1 to 575 cubic metres of water per ton of CO_2 captured, depending upon the energy source and technology used. Adding CCS to coal and natural gas plants will increase the consumption of water resources to varying degrees depending upon the capture technology used and the cooling system installed at the plant. Magneschi et al. (2017) estimated that this typically ranges between 20 and 60 per cent of water consumption for plants that use wet recirculating cooling processes. Byers et al. (2016) found ranges of increased cooling water demand for power plants adding CCS across several studies to be 44–140 per cent. This increased water demand is already viewed as a potential barrier to uptake, particularly if no additional efficiency measures are taken (Byers et al. 2016). There is also potential to add CCS to reduce industrial production emissions, for example in cement and steel production (IEA 2021c). Rosa et al (2021) found that widespread use of CCS to achieve the climate targets found in some scenarios could potentially double overall freshwater demand globally. Bioenergy with CCS (BECCS), which has the highest potential water demand, is covered in section 7.3.

Box 7.2. Measurement units for energy, electricity, fuels, and heating

Energy consumption is categorized primarily by the use of fuels for transport, buildings, industries, and power generation. Electricity and heat generation are measured in terms of joules, watts (capacity to produce a certain amount of electricity), and watt hours (provision of electricity of a certain amount over time). Energy consumption from fuels is measured in tons of oil equivalent (TOE), defined as the amount of energy released from burning one ton of crude oil. The energy requirements to produce electricity can be converted to TOE for comparison and these are used generally to measure energy supply and use. Globally, in 2018, 20 per cent of total final energy consumption was used for electricity generation from renewable sources (IEA 2020b). This was projected to rise to 27 per cent in 2021 (IEA 2021c).

7.2 Hydropower

7.2.1 Mitigation potential

Hydropower plants generate electricity by using flowing water to spin a turbine and connecting this to a generator. The main types of hydropower technology include a) run-of-the-river systems, which channel flowing water from a river through a canal or penstock; b) storage hydropower, which are larger systems that use a dam to store water in a reservoir and release water through a turbine; and c) pumped storage hydropower, which pumps water between a lower and upper reservoir and uses surplus energy at times of low demand.

Hydropower is currently the largest source of renewable electricity generation in the world and second-largest renewable energy source to bioenergy. The 2022 hydropower status report (IHA 2022) states that installed capacity for hydropower worldwide was 1360 GW and, respectively, 4250 TWh of electricity generated in 2021. Hydropower accounts for about 45 per cent of current renewable energy generation, and 16 per cent of total electricity production (IEA 2021e). Over the past five years, hydropower capacity has increased by about 2 per cent annually (IHA 2021). The International Hydropower Association (IHA) states that an additional 500 GW of installed capacity is in the pipeline today, and IEA projects an additional growth of 17 per cent over current capacity during the next decade, the majority of which will be in Africa and East Asia (IHA 2021; IEA 2021i). In some scenarios for achieving emission reduction targets in the energy sector, the expected increase is even more significant, ranging from a further 850 GW to 1,300 GW of additional installations. IEA net zero scenarios project hydropower production to double by 2050 (IEA 2021f) and the IRENA Global Renewable Outlook - Energy Transformation 2050 scenarios for a renewable energy mix required to achieve net zero emission targets for 2050 estimated a 60 per cent overall increase in hydropower and 200 per cent increase in pumped hydropower annual production over the next 30 years (IRENA 2020).

Hydropower is generally categorized as a low-emission energy technology (IHA 2021; IEA 2021i); however, there is debate as to whether the emissions from hydropower reservoirs are measured sufficiently. The GHG emissions from hydropower production differ based on the conditions surrounding the hydropower plant and reservoir, which makes it difficult to use average emission rates at project or country level (Bruckner et al. 2014; Kumar et al. 2011). (Ubierna et al. 2022) assessed global median life-cycle GHG emissions to be 23 grammes CO_2 equivalent per kilowatt hour, based on analysis of nearly 500 hydropower storage projects. Emissions from hydropower across the life cycle of plant construction and operation are influenced by a number of factors (Pfister and Nauser 2020). Emissions result when organic material settles and decomposes in the reservoir water and releases CO_2 and methane. Traditional estimates of direct emissions from hydropower may underestimate the actual emissions, as assessments can lack data or consideration for methane emissions in reservoirs, the effects of the accumulation of GHGs over time, and indirect emissions from hydropower plant construction (Ocko and Hamburg 2019). These factors can lead to a wide variance of emissions resulting from hydropower that are affected by location, design, and use of plants, and, in some cases, can negate positive mitigation impacts. There are

The Mooserboden reservoir walls of the Kaprun hydroelectric plant, Austria. Source: Shutterstock.

Table 7.1. Regional installed capacity and annual hydropower generation in 2021

REGION	INSTALLED CAPACITY (GW)	POWER GENERATION (TWh)
Africa	38	146
Asia-Pacific	523	1639
South and Central Asia	157	537
Europe	255	659
North and Central America	206	702
South America	177	658
Global	1360	4250

Source: International Hydropower Association (2022).

also indirect emissions that result from different stages across the life cycle of hydropower installations, such as construction, operation, and decommissioning of plants (Kumar et al. 2018). Improved data and measurement of emissions resulting from hydropower installations and operations are needed to enable net emission reductions (see Chapter 5).

7.2.2 Geographical distribution

Hydropower is developed and in operation in all major regions, with the largest installed capacity in East Asia and the Pacific (see table 7.1). China, Brazil, United States of America (USA), Canada and India have the highest amounts of installed national capacity. Within the next five years, the Asia-Pacific region, particularly China, is expected to see the greatest development of additional hydropower (over 65 per cent of projected growth), followed by Latin America, North America and Europe (IEA 2021i). The regions with the greatest future potential and projected growth of hydropower are East Asia and the Pacific, Africa, and South and Central Asia (IHA 2022).

7.2.3 Water dependence and impacts

The impacts and dependence of hydropower on water are direct and well known. Hydropower produces energy using water, so is entirely dependent on this resource. Large volumes of water move through hydropower systems to generate power and this power generation potential is heavily impacted by the quantity of water flowing through the system. Potential changes in the volume of water due to climate change (increasing evapotranspiration and decreasing water inflow) or withdrawals for other uses must be considered to ensure that the actual energy generation of a hydropower plant is close to the assessed installed capacity. Reservoir-based hydropower infrastructure blocks, diverts, and changes the natural flow of a river, fundamentally impacting surrounding ecosystems. This can negatively affect fish migration and breeding, with knock-on impacts on overall ecosystem health and less fish for human consumption. Reductions in water and sediment flows resulting from dams can have further impacts on downstream wildlife populations and habitats. Some water is lost through evaporation during storage and use, and this varies according to different conditions (Scherer and Pfister 2016). Jin et al. (2019) found the median level of water consumption across several studies to be 4,961 litres per megawatt hour of electricity produced. There is a need for improved data on global water use and the impacts of hydropower. While there are studies to assess water use and consumption in specific hydropower installations, there is such high variance that the impacts are difficult to project. The variation in hydropower water use estimates also stems from discrepancies in the ways that water use and consumption are defined, such as differences between accounting for gross or net evaporation, or attributions of evaporation in reservoirs between various users and causes (Larsen et al. 2019; Engström et al. 2019; Herath et al. 2011). As a result, water use and consumption for hydropower is sometimes omitted in global assessments (e.g., IEA 2018). Recent studies in China (Tian et al. 2021) and the USA (Zhao and Gao 2019) have estimated that water loss through evaporation from reservoirs is significant, reaching several hundred cubic kilometres globally each year.

7.2.4 Co-benefits and trade-offs

Hydropower plants and multi-purpose water infrastructure can provide additional co-benefits such as water storage and flood protection. Hydropower is a large industry, employing over 2 million people worldwide (IRENA 2021). Reservoir and pumped storage hydropower can be used to provide flexibility in energy systems enabling an increased share of variable renewable energies. This can enable the expanded use of solar, wind, and other clean energy sources. Hydropower can also be used as a potential energy source to develop green hydrogen fuels in the future (IHA 2021).

There can also be significant social and environmental impacts of hydropower development. Environmental issues can include negative impacts on hydrological regimes, water quality, sedimentation, biodiversity, disruptions to fish migration and spawning, and others, as described in the previous section (Kumar et al. 2011). Social impacts can include required (and sometimes forced) relocations of populations living in areas surrounding hydropower construction. While dams can in some cases support flood protection downstream, there can also be higher risks of flooding upstream in areas surrounding constructed reservoirs, as well as more devastating flood events occurring if there are dam breakages. Trade-offs between benefits provided through energy generation and environmental or social consequences downstream can also lead to tensions and challenges between riparian countries sharing a river system where the hydropower is installed (Brunner et al. 2019; Elsayed et al. 2022; Dombrowsky and Hensengerth 2018).

7.2.5 Potential implications for governance

The effective planning, design, and management of hydropower is essential. Emissions from hydropower facilities with poor siting, design, and management may be underestimated to the extent that they provide limited or even no climate mitigation benefits compared with alternatives (Ocko and Hamburg 2019). Improved estimates of potential impacts on nitrous oxide and methane emissions from existing and potential new hydropower reservoirs are needed. Assessment of potential climate impacts on hydropower across the lifecycle of construction and operations is critical and requires a thorough analysis of various models. Studies from IEA in Asia (IEA 2021b) and Latin America (IEA 2021a) project a decrease in hydropower generation potential due to climate change, and recommend building more robust climate databases and strengthening climate impact assessments. Additional actions to integrate climate resilience in early stages of hydropower projects include the creation of climate-resilient construction codes, and mandatory climate risk assessments and emergency response plans (IEA 2021b). Evaluation in advance of investment should be made to ensure that the environmental and social costs do not outweigh the potential benefits gained through the energy generated. The potential inequities of the distribution of benefits and negative impacts between groups must also be considered in this evaluation. This requires attention on several areas that need careful consideration, such as the impacts on local communities, water balance and ecosystem alterations caused by existing and new hydropower developments; the impact of climate change on hydropower generation during its operational lifetime; potential increased emissions from water bodies that result from alterations caused by hydropower installations; and effective processes in transboundary basins to ensure benefits are shared and downstream impacts accounted for. Some applications of best practice to assess and minimize environmental and social impacts can be found, including hydropower sustainability tools (IHA 2021), which include guidance on actions to take regarding resettlement, biodiversity, and downstream flow impact reductions and sediment management. Guidance materials include risk management guides and sustainability standards to rate environmental, social, and governance performance produced by IHA and the World Bank (e.g., Lyon 2020).

7.3 Bioenergy

7.3.1 Mitigation potential

Bioenergy currently accounts for about 10 per cent of total global energy supply (IEA 2021h). It is used for different purposes, such as electricity generation, transport, and heating. Aside from traditional cooking and heating with biomass, the pathways used for conversion of biomass into energy are commonly categorized as first- and second-generation bioenergy

Table. 7.2. Characteristic differences between first- and second-generation biomass feedstock.

CHARACTERISTIC	FIRST-GENERATION BIOENERGY	SECOND-GENERATION BIOENERGY
Feed stock	Sugar/starch rich fruits (e.g., sugarcane, sugar beet, maize), oil-fruits (e.g., rapeseed, sunflower, soy, oil-palm)	Lignocellulose biomass (e.g., miscanthus, switchgrass, willow, poplar, eucalyptus), biomass residues from agriculture/forestry, solid waste
Processing pathways	Fermentation, chemical conversion of oil to biodiesel	Combustion, thermo- and biochemical conversion
Target energy carrier	Bioethanol, biodiesel	Electricity/heat, hydrogen/bioethanol
Potential for carbon capture and storage	Low	High (combustion/heat/hydrogen), low for bioethanol

Source: Based on Lee and Lavoie (2013)

(Table 7.2). First-generation bioenergy refers to the production of fuels (bioethanol and biodiesel) from oil fruits (e.g., rapeseed, oil palm, sunflower) or sugar plants (e.g., sugarcane, sugar beet). Second-generation bioenergy uses biomass from plant lignocellulose, solid waste or residual biomass (from forestry or agricultural activities) that is generally converted into electricity or heat (and in some cases bioethanol). Combustion of biomass is performed in a similar way to that of coal-fired power generation (Ali and Kumar 2017).

In 2020, 7 per cent of liquid fuels for road transport came from biofuels, and over 90 per cent of those fuels came from first-generation sources, such as bioethanol and biodiesel (IEA 2021h). Currently, 330 million hectares of arable land is dedicated to the production of energy crops (IEA 2021h). Due to conflicts with food production, land, and water resources, expansion of energy crops for direct conversion to fuels is limited in most scenarios for climate mitigation (IEA 2021f; IRENA 2020). In 2018, global bioenergy production was 55.6 exajoules (EJ) (World Bioenergy Association 2020). Biofuels are the third-largest source of renewable electricity production at 637 TWh, accounting for 9 per cent of renewable electricity production and over 2 per cent of total electricity production. Two thirds of this is generated from solid biomass, with the remaining amount coming from municipal and industrial waste and biogas (World Bioenergy Association 2020). Bioenergy provides 95 per cent of renewable sources for heating and cooking, and 10 per cent of total energy for heating (IEA 2020a). In the scenarios for energy production evaluated by IPCC (Rogelj et al. 2018), global annual bioenergy production will account for 118–312 EJ in the year 2050, with average values of 200 EJ. The use of modern bioenergy is projected to grow substantially under many low-emission transition projections. The use of modern forms of solid bioenergy increases by 30–70 per cent by 2030 across IEA low-emissions and net zero emissions scenarios (IEA 2021g). Expansion of biogas for clean cooking in the IEA net zero emissions projections has the potential to serve 400 million people by 2030.

Bioenergy GHG emissions occur during land-use conversion and the harvesting, transport, processing, and conversion (through e.g., burning) of biomass. These emissions may be offset to various degrees by CO_2 absorption that takes place during crop growth (Welfle et al. 2020; US EIA 2021). The emission factor of using biomass to produce fuel, heat, or electricity can thus vary significantly. Life-cycle emissions per unit of electricity produced from biomass is currently significantly higher than for all other renewable alternatives (Rogelj et al. 2018).

7.3.2 Bioenergy with Carbon Capture and Storage

Bioenergy with Carbon Capture and Storage (BECCS) is required for low-emission bioenergy production and can potentially achieve negative emissions. BECCS is a negative emission technology that may sequester significant amounts of carbon from the atmosphere, while also using biomass to produce electricity or fuels. BECCS combines second-generation bioenergy (primarily through the production of biomass on plantations from plant lignocellulose) with the industrial combustion/fermentation and subsequent extraction and storage in geologic reservoirs of (part of) the carbon sequestered (Lenton 2010; Azar et al. 2006; Carbo et al. 2011; Caldeira et al. 2013). To avoid competition with food production, this biomass generally should not be produced on land otherwise used for primary crop production. BECCS is a relatively recently proposed approach, compared to first-generation bioethanol/biodiesel production (Laude et al. 2011), which is still under research and testing with no current large-scale deployment (Fajardy et al. 2019; Gough and Mander 2019). CCS techniques capture CO_2 from industrial processes. For BECCS this happens in the phase of biomass combustion for electricity generation or in the chemical conversion processes to biofuels. The CO_2 is compressed and pumped into geologic reservoirs with the aim to provide long-term storage (Bui et al. 2018). These CCS techniques remain at a stage of modest demonstration (Gough and Vaughan 2017) and large-scale field studies for BECCS process chains are missing (Fuss and Johnsson 2021). Electricity generation in this process is generally thought to have much higher carbon conversion efficiencies than liquid biofuel production (Lenton 2010; Fajardy et al. 2019).

7.3.3 Geographical distribution

The largest biofuel-producing regions currently include Brazil, China, India, and the USA, as well as Southeast Asia. China, Brazil, and India produce the most ethanol (8, 6 and 2 billion litres respectively), and the USA and Association of Southeast Asian Nations (ASEAN) countries produce the most biodiesel and hydro-treated vegetable oils (5 and 6 million litres respectively) (IEA 2021h). The global potential development of BECCS is determined by the availability of suitable land, water, and climate conditions (Ai et al. 2021; Bruckner et al. 2018; Stenzel et al. 2021a).

7.3.4 Water dependence and impacts

The cultivation of biomass for conversion to fuel or electricity requires substantial amounts of freshwater and land to support the plant growth. This water can come from rainfall or can be taken from rivers, lakes, reservoirs, or aquifers for irrigation. For BECCS, additional water is required to support the CCS performed at the power plant, which is estimated at roughly 450 cubic metres of water to sequester 1 ton of CO_2 (Smith et al. 2015). To maximize biomass yields, the cultivated plants should combine fast growth and robustness to the local climate. Management (e.g., use of fertilizer and irrigation water) plays a key role in both the potential development of biomass and its impact on water sources (see Box 7.3).

Soil erosion can result from land-use change, e.g., when natural forest is converted to cropland, with likely impacts on streamflow (including increased risk of floods) and groundwater recharge. Changes in vegetation

Train delivering fuel to the biomass plant at Drax power station, UK, which is currently investing in BECCS infrastructure.
Source: Shutterstock.

also affect moisture availability and recycling, not only locally but also in remote regions that are linked through the climate system (Wang-Erlandsson et al. 2017). Agrochemicals and pesticides used in biomass cultivation can cause freshwater ecotoxicity (Nordborg 2013).

Irrigation is probably needed in many areas to maximize the productivity and CO2 sequestration capacity of the vegetation. Land constraints on the cultivation of future second-generation bioenergy for BECCS are likely to increase dependency on irrigation water (Jans et al. 2018). The potential requirements for freshwater irrigation of biomass plantations are significant and a key factor determining the extent of their development in future. Development of biomass will also depend on the demands for water in different regions (See Box 7.3.).

7.3.5 Co-benefits and trade-offs

Bioenergy production is currently a significant source of income and jobs, employing over 3.5 million people globally (IRENA 2021). The conversion of biomass residues from agriculture and forestry, solid waste and sludge from municipal and industrial processes into fuel or electricity sources can transform potential environmentally harmful wastes into beneficial economic goods.

BECCS systems are designed to provide co-benefits that accelerate emissions reductions and concentrations by providing materials for the production of electricity or fuel, as well as sequestering carbon. Like hydropower and geothermal energy, this can also serve as a baseload to grid with solar and wind production. If implemented in a socially-ecologically sustainable manner, it can also enhance productivity of certain land uses and provide economic benefits and agricultural livelihoods. The very high demand for water and land however means that significant trade-offs need to be considered. Luderer et al. (2019) estimated that generating electricity from BECCS occupies 20 times more land area than hydropower, or coal with CCS, and two orders of magnitude more than wind and solar PV. Land-use changes can also lead to loss of natural wildlife, habitat, and reduced biodiversity. Creating biomass plantations is an intervention into ecosystem and landscape structure and functioning, and thus involves environmental impacts (Heck et al. 2016).

Projections on the potential for negative emissions that can be delivered from large-scale biomass plantations must consider the likely constraints faced by limited water and land availability in many regions (e.g., Heck et al. 2016). Investment in BECCS that seek only to maximize their potential for energy generation and carbon sequestration on existing land could result in global water withdrawals of up to 9,000 cubic kilometres per year by the end of the century – more than the current water use by agriculture, industry and households (Stenzel 2021). Demand for water and land for BECCS need to be evaluated to determine its potential implications and viability.

7.3.6 Potential implications for governance

As detailed above, climate mitigation contributions from large-scale biomass production may partly fail due to water limitations, or their implementation may adversely affect water availability. It is therefore imperative that water issues are considered in any deployment of such mitigation measures. This calls for integrative approaches that not only aim for maximizing negative emissions but also account for the preservation of aquatic ecosystems (such as in the European Water Framework Directive[1] or the Brisbane Declaration and Global Action Agenda on Environmental Flows[2]) and sustainable water management for both biomass plantations and agricultural areas. Integrative approaches can enable available water to be used more effectively, boost biomass production, and create synergies across multiple Sustainable Development Goals (SDGs), including targets for food, water, and climate security (Jägermeyr et al. 2017). Stenzel (2021b) highlights that substantial reductions in water withdrawals could be achieved if less plantations were irrigated and the carbon conversion efficiency was improved, thus enabling more production and sequestration with lower impacts on water. Large-scale field studies for the BECCS process chain are missing and are needed to fill the current implementation gap (Fuss and Johnsson 2021).

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1. Declaration, B., 2007, September. The Brisbane Declaration: environmental flows are essential for freshwater ecosystem health and human well-being. In 10th International River Symposium, Brisbane, Australia (pp. 3-6).
2. Directive 2000/60/EC of the European Parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy (OJ L 327, 22.12.2000, p.1).

Box 7.3. Assessing potential future constraints and applications of BECCS

Existing estimates of global freshwater quantities required for large-scale second-generation biomass plantations dedicated to BECCS, of either woody (e.g., willow, poplar, eucalyptus) or herbaceous (e.g., switchgrass, miscanthus) type vary significantly. These have been produced mainly from scenario studies that consider BECCS as part of a portfolio of climate change mitigation options. The studies explicitly or implicitly address the issue of freshwater requirements. A recent literature review of 16 available global model-based assessments found that estimates of water withdrawal for irrigation of BECCS plantations vary from 128 to 9,000 cubic kilometres per year (km^3/y) (Stenzel et al. 2021a); values for water consumption are of similar orders of magnitude. The large range originates from different model parameters and scenario set-ups.

A further study (Ai et al. 2021) concluded that constraints for irrigation water supply will limit the actual land available globally for sustainable development of BECCS much more than most scenarios currently predict. If land in areas with water stress and withdrawal of non-renewable water are removed from scenarios, the water demand of BECCS is limited to 300 km^3/y instead of around 1,400–3,900 km^3/y. This has significant implications on the mitigation potential of BECCS development in the coming years.

Stenzel et al. (2019) distinguished the contribution of different factors to the potential freshwater for irrigation of biomass plantations in a framework of systematic simulations with one global hydrological and vegetation dynamics model. The study considered, both singly and in combination: a) limits to water withdrawals imposed by environmental flow requirements (preserving a monthly minimum flow to maintain riverine ecosystems); b) different carbon conversion efficiencies; and c) sustainable on-field water management options including ambitious levels of water harvesting, soil conservation, and irrigation system upgrades on both biomass plantations and food-producing cropland. Current agricultural land and land worthy of protection were excluded as potential plantation areas. On the remaining land, either woody or herbaceous biomass plantations were assumed to grow if needed for achieving the sequestration demand and, if climatic conditions allowed, giving preference to plant types with high water-use efficiency.

The simulations showed that unconstrained withdrawals of available freshwater (scenario IRR) on the areas considered for irrigation of biomass plantations would result in a global water use of almost 2,400 km^3/y, if the plantations were to sequester 255 Gt carbon by 2100 (Figure 7.3). This would equal around 80 per cent of the sum of current agricultural, industrial, and domestic water withdrawals. Scenarios that account for environmental flow requirements or more effective water management suggest a lower pressure on freshwater systems of this mitigation option. Accounting for environmental flows (scenario EFRs) would reduce the withdrawal to slightly below 1,500 km^3/y; however, the water and land available under this constraint would not be sufficient to support irrigation to the extent required for meeting the plantations' expected contribution. If more effective water management was implemented in addition (scenario WM), values would somewhat increase again as more water would become available downstream, enabling the sequestration demand to be almost met. Substantial further reductions in water withdrawals to around 400–700 km^3/y could be achieved if less plantations were irrigated, and the carbon conversion efficiency was improved (Stenzel et al. 2019).

While these simulations elucidate some water-related trade-offs and co-benefits involved with bioenergy production, any further water use would come on top of (or compete with) the demand from other sectors (Figure 7.3). This will potentially increase overall water stress, which is already high in many regions of the world. To provide the context of regional and global water stress, Figure 7.4 highlights areas where irrigation for bioenergy production would increase existing water stress or newly introduce stress (defined as a withdrawal/availability ratio). The spatial patterns are derived from a further model- and scenario-based study by Stenzel et al. (2021a), in which – other than in the study referred to above – future land use was allocated based on an economic optimization of the agricultural sector including biomass plantations, with irrigated fractions of the plantations assigned afterwards.

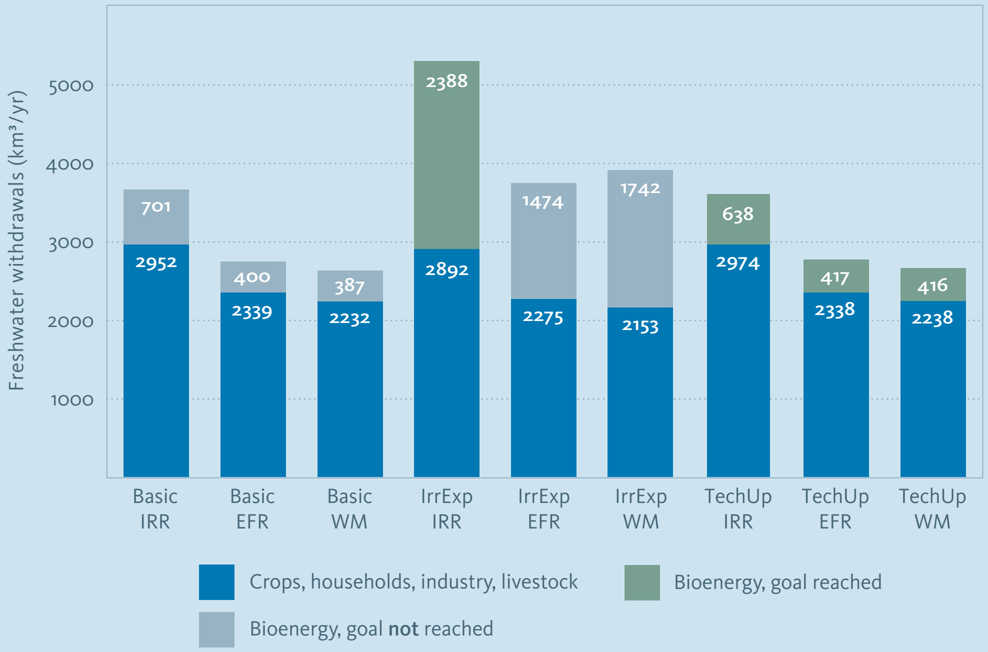

Figure 7.3. Annual (mean 2090–2099) freshwater withdrawal for irrigation of bioenergy plantations on top of withdrawals for agriculture/livestock, industries, and households, for different scenarios. Source: Stenzel et al. (2019). The assumed underlying total carbon sequestration goal of 255 Gt carbon (following a trajectory from 0.54 Gt carbon in 2030 to 5.45 Gt carbon in 2100, after Rogelj et al. (2015) required for limiting global warming to 1.5°C cannot be reached in all scenarios (green versus grey). The value for withdrawals in other sectors varies slightly among scenarios, as irrigation of plantations is simulated to compete with them. Improved water management (in some scenarios) is assumed to be applied on both the plantations and cropland. Baseline scenario (Basic): carbon conversion efficiency = 50 per cent and maximal irrigation fraction = 33 per cent; variants: in TechUp the former is 70 per cent, in IrrExp the latter is 100 per cent; while IRR assumes unconstrained withdrawals, environmental flows are respected in EFR, and WM additionally assumes improved water management.

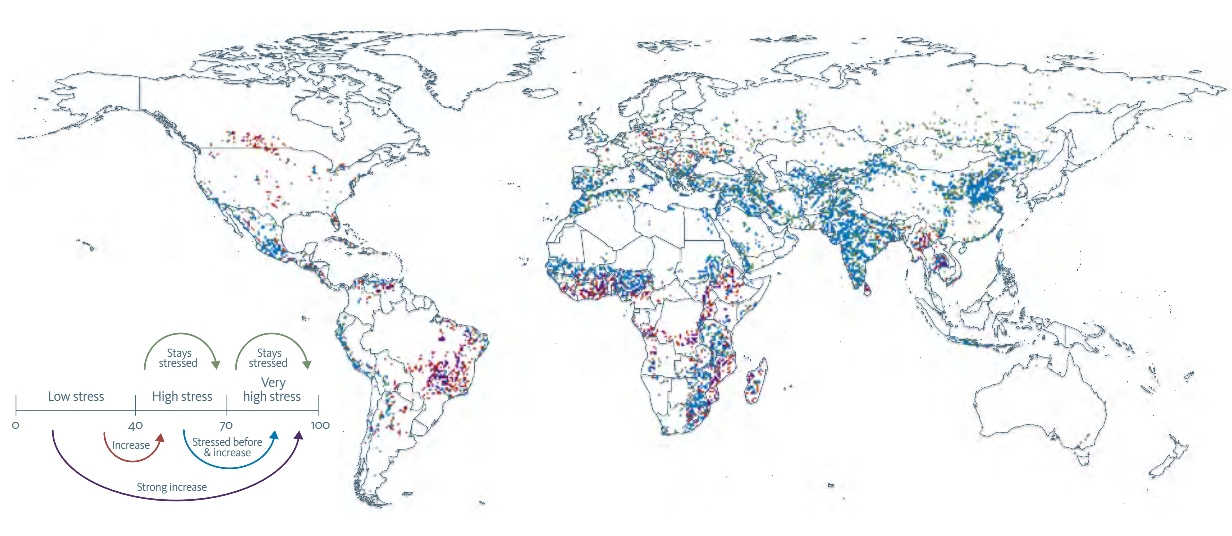

Figure 7.4. Regional changes in water stress class (mean 2090–2100) when adding irrigation of 30 per cent on BECCS plantations in an SSP2–RCP2.6 scenario (Frieler et al. 2017); total area, 616 million hectares under climate change according to the HadGEM2-ES model, after simulations from Stenzel et al. (2021a). Mean annual stress is calculated per 0.5°C grid cell as the percentage ratio of total water withdrawals (bioenergy, agriculture, industries, households) to available river discharge. Shown is where the water stress newly surpasses critical thresholds of 40 per cent (increase, orange colour) and 70 per cent (stressed before and increase, blue colour) respectively, surpassed both thresholds (strong increase, purple colour), or where it persists (stays stressed, green colour) compared to rainfed bioenergy.

Box 7.4. Green hydrogen and water

Hydrogen is an energy carrier, not an energy source. Hydrogen can be extracted from fossil fuels, biomass, or water (or a combination), and the emissions resulting from its use depend entirely on the source and the energy used in the process to extract it (similar to electricity). The global production of hydrogen accounts for 830 million tonnes of CO_2 emissions annually as the vast majority is produced using fossil fuel sources, e.g., coal and natural gas (IEA 2019). This is labelled as grey hydrogen if generated by fossil energies, or as blue if CCS is also applied. Blue hydrogen at present may not reduce the carbon intensity of energy use below that of natural gas (Howarth and Jacobson 2021). Green hydrogen, which is produced using renewable sources of clean energy, currently provides less than 1 per cent of total hydrogen production (IRENA 2020).

Currently, hydrogen energy is used mainly in industrial settings and produced with sources from natural gas and coal. Its future applications are envisaged in transport, buildings, and power generation (IEA 2019) using non-fossil-fuel sources and production processes powered by clean energies. It is anticipated that hydrogen will provide a critical element of future energy delivery systems in line with reduced emission targets. The European Union refers to green hydrogen as “the missing piece of the puzzle” in a fully decarbonized economy (EC 2020). Hydrogen is similarly characterized by IRENA in its global renewable energy outlook as a pillar for transformative energy futures, where they forecast exponential growth as a requirement for achieving zero net emissions targets by 2050. Current production levels for green and blue hydrogen energy are less than 2 million tons annually. An increase to 240 million tons by 2050 is required in the IRENA net zero scenarios (IRENA 2020). This would also require 7,500 TWh of annual renewable power producing hydrogen energy (raised from 0.26 TWh in 2016) and increased capacity of electrolysers to 1,700 GW (raised from 0.04 GW in 2016). Land and water demand for the electricity production required to synthesize hydrogen needs to be considered as this differs significantly between energy sources and dramatically effects the overall environmental impacts of the hydrogen produced (Mehmeti et al. 2018; Trainor et al. 2016).

Water also plays a crucial role in providing hydrogen when it is extracted through water electrolysis. Every unit of hydrogen generated in this way consumes an estimated 9 units of water (Webber 2007; Beswick et al. 2021). The amount of water required to realize the potential scale of the expansion of hydrogen energy may pose potential constraints or trade-offs between uses (Webber 2007; Beswick et al. 2021). Some studies note that large-scale expansion of hydrogen energy for use in urban areas could also lead to risks of competition with drinking water sources (Oldenbroek et al. 2016). Many scenarios project solar and wind power generation being stored in hydrogen and shipped as clean energy supplies over much larger distances than electricity networks can send (e.g., IRENA 2020). This has potential for relative water savings at global or regional levels, as solar and wind power generation require less water than most fuel alternatives (Beswick et al. 2021). However, this also requires solar and wind plants to be located near a water source. This can be done for offshore wind power, but this is projected to expand at a much lower overall rate, it is currently is more costly to build and operate, and it may require desalination if using seawater (Sayed et al. 2021). Some of the greatest potential for solar power is available in arid environments and access to water sources for water electrolysis may be limited (ESMAP 2020). This means that water will be an important factor in planning the potential expansion of green hydrogen in the future.

7.4 Geothermal energy

7.4.1 Mitigation potential

Geothermal energy derives from heat below the earth’s surface that is carried up by hot water and/or steam. Depending on its characteristics, geothermal energy can be used for heating and cooling purposes, and can be harnessed to generate clean electricity. However, high or medium temperature resources are needed for electricity, which are usually located close to tectonically active regions.

Geothermal energy is a renewable resource that can also serve as a baseload energy source for intermittent sources like solar and wind. Annual global production

Svartsengi geothermal power plant in Iceland. Source: Shutterstock.

of geothermal energy for electricity is under 15 GW, while providing 46,000 terajoules for heating (which is roughly the same as biogas used for heating) (IEA 2020a). It has very low CO_2 emissions, estimated by IRENA (2017) to be 8 grammes per kilowatt hour of energy produced.

There is considerable potential for expansion of geothermal power, as there is exponentially more energy contained within the heat inside the earth's surface than can be obtained with all the oil and gas resources on the planet (IRENA 2017). Annual growth of geothermal energy (about 3 per cent) is slower than alternatives such as solar and wind. Current costs for construction, inspection, and drilling, as well as the required detailed oversight of social and environmental risks, are slowing the expansion of geothermal plants.

7.4.2 Geographical distribution

Geothermal plants are located in areas with molten rock that are close to the earth's surface and so relatively easy to access. Indonesia holds as much as 40 per cent of global geothermal reserves with potential for development and has the largest planned expansion in the near future (Ayuningtyas et al. n.d.). Other nations where geothermal energy is most widely developed include Costa Rica, El Salvador, Iceland, Italy, Japan, Kenya, Mexico, New Zealand, Nicaragua, Philippines, Turkey, and USA (IRENA 2017).

7.4.3 Water dependence and impacts

Geothermal energy is derived from pools of water heated by magma below the Earth's surface, so it is directly water dependent. The operation of geothermal power plants also requires water. The amount of water depends on several factors, including the size of the plant, technologies used, operating temperature, and cooling process used. When water is used for cooling and re-injection, geothermal can be water resource intensive (see also concentrated solar power [CSP], nuclear, etc.). If geothermal fluids are used instead of external water resources, then water use declines significantly (Jin et al. 2019; Union of Concerned Scientists 2014). Considerable amounts of water can also be required during the drilling and construction phases. Jin et al. (2019) estimated the median water demand for geothermal energy was 1,022 litres per kilowatt hour, though the factors listed above lead to a considerable range of values.

Geothermal power plants can have impacts on both water quality and level of consumption. Several studies have raised water pollution and ecosystem degradation as significant environmental impacts of geothermal energy system development (Sayed et al. 2021). These can be caused by contaminated wastewater discharges and by thermal pollution effects (e.g., sudden discharge of warm or cold water into water bodies). Hot water pumped from underground reservoirs often contains high levels of sulphur, salt, and other minerals. This water is generally kept within a closed-loop system, but there are risks of contamination if this system fails (Bošnjaković et al. 2019). Potential risks with implications for surface- and groundwater include contamination of groundwater with drilling fluids (during the drilling process), depletion and warming of groundwater during the mass withdrawal operations, and contamination of groundwater and surface waterways in the disposal of waste liquids (from both surface disposal and reinjection processes) (Bošnjaković et al. 2019).

Some geothermal plants emit small amounts of mercury, which must be mitigated with appropriate filtering technologies. Scrubbers can reduce air emissions, but they produce a watery sludge composed of the captured materials, including arsenic, chlorides, mercury, nickel, silica compounds, sulphur, vanadium, and other heavy metals. This toxic sludge must be disposed of at hazardous waste sites (Union of Concerned Scientists 2014).

7.4.4 Co-benefits and trade-offs

Additional potential environmental impacts can result from geothermal energy and should be evaluated during planning, development, and operations. These include potential geological hazards (such as landslides or tremors), air pollution, land subsidence following removal of steam and mass fluids, land-use impacts and drilling that can cause disturbance to people and wildlife and damage biodiversity, and release of gases and solid wastes that can harm the health of workers and other people in the area (Sayed et al. 2021). Land-use changes required for the development of geothermal energy plants can also be significant. Examples that have prevented development in Indonesia, for example, include prospecting areas including conservation forests, ancestral land rights, impacts on local water resources, and cultural objections to drilling through land (Ayuningtyas et al. n.d.).

A key benefit of geothermal energy is its ability to provide a baseload for the grid to support the use of other intermittent renewable electricity technologies, such as wind and solar PV. Hybrid approaches can also be used to enhance efficiency and reduce land and resource requirements of the geothermal plants by, for example, using wind or solar PV to pump fluids, and solar thermal plants to heat the underground reservoirs.

7.4.5 Potential implications for governance

Well-managed geothermal energy generation provides an opportunity for low-emission energy development and is particularly abundant in certain regions. Due to significant potential environmental risks, thorough environmental impact assessments and continuous monitoring are necessary. Management and planning practices make a considerable difference to risk mitigation, including such issues as proper site allocation and placement of injection wells. Customized plant design is also needed to ensure that construction and operational guidelines are suited to the specific surrounding environment (Sayed et al. 2021).

7.5 Nuclear power

7.5.1 Mitigation potential

Nuclear power provides about 10 per cent of global annual electricity and 5 per cent of total energy supply, representing an approximate annual production of 700,000 kilogrammes of oil equivalent (IEA 2020a). Nuclear power does not create direct emissions from its operations, although the mining and refining processes of uranium ore and the construction of the power plant itself require energy, so creating indirect CO_2 emissions. According to an IPCC report (Bruckner et al. 2014), CO_2 emissions from nuclear power are 12 grammes per kilowatt hour, making it the second-lowest emitter (after wind power) of the major sources of electricity.

The World Nuclear Association (2019) states an ambition (entitled 'Harmony') to support the achievement of the Paris Agreement targets by increasing nuclear power production by 1,000 GW by 2050 to provide 25 per cent of global electricity. However, nuclear power presents certain environmental, social, and security risks that pose some of the starkest trade-offs and divergence of views from the global community on its role in the future energy mix. For these reasons, multiple global scenarios, such as the IEA net zero emissions by 2050 roadmap, forecast a lower expansion to keep nuclear at roughly 10 per cent of global electricity production (Rogelj et al. 2018; IEA 2021f).

7.5.2 Geographical distribution

Physical geography or regional climates and environments are not important factors in the development of nuclear power. There are over 30 countries with nuclear power plants, but not all are in operation. Most of the countries with nuclear power plants are located in Europe, North America, and East and South Asia. The countries with the largest generation are the USA, France, China, Russia, Korea, and Canada. The countries with the highest ratio of energy production from nuclear energy are France (70 per cent), Slovakia (53 per cent), Ukraine (51 per cent), Hungary (48 per cent), Bulgaria (40 per cent), and Belgium (39 per cent) (IAEA 2021).

7.5.3 Water dependence and impacts

Like other thermo-electric power plants, nuclear power generation involves boiling water to make steam and then using water to cool the steam after it runs through the turbine. For safety and cost reasons, dry cooling is not used in nuclear plants. Jin et al. (2019) found the median water use for nuclear power plants to be 2,290 litres per megawatt hour and that it is slightly more water intensive than all other thermo-electric types of plant. Reduced availability of water, caused in part by climate change-induced reductions in rainfall in some areas, is leading to increased frequency of nuclear power outages (Ahmad 2021). While several factors affect total water requirements, the largest factor is the type of cooling system chosen. Nuclear power with once-through cooling systems have been assessed as having the highest demand for water withdrawals since once-through cooling uses more water than recirculating systems (Ali and Kumar 2017). In some cases, seawater is used for cooling and this lowers freshwater demand significantly.

Water is also used in the fuel extraction process, which includes the mining, processing, milling, enrichment, and fabrication of uranium into fuel. Water-based storage pools may also be used for storage of nuclear fuel after it is used. Further, nuclear plants require access to large emergency sources of water (called ultimate heat sinks) in case of accidents, when a plant may be shut down and require continued cooling.

Thermal pollution (e.g., sudden discharge of warm or cold water into water bodies) harms water quality and ecosystem health (see Box 7.5.). Accidents or failures at nuclear plants (e.g., the Fukushima Daiichi nuclear power plant disaster of March 2011 in Japan), can lead to the discharge of radioactive waste or water into oceans and freshwater bodies, posing risk of significant harm to ecosystem and human health that can potentially last for decades (Lu et al. 2021).

7.5.4 Co-benefits and trade-offs

Like hydropower and geothermal power, a key benefit of nuclear energy is its ability to provide a baseload for the grid to support the use of intermittent renewable electricity technologies, such as wind and solar PV. There are also potential opportunities to capture and utilize heat generated at nuclear power plants for thermal, process, and district heating; however, social acceptance of this practice has limited its applications to date (Royal Society 2020). Radioactive materials and waste created through nuclear power generation and uranium mining pose significant potential risks to environmental and human health. Radiation exposure from direct discharges of radioactive waste result in long-term damage to ecosystems and communities (Luderer et al. 2019; Lu et al. 2021).

High perceived risk and moral opposition to nuclear power in segments of the population can lead to significant social costs or create political barriers to its uptake (De Groot and Steg 2010). The development of nuclear power can also have significant implications for global, regional, and national security, and there is generally a high correlation between the development of nuclear power generation capacity and the proliferation of nuclear weapons (Sorge and Neumann 2021).

7.5.5 Potential implications for governance

Water is a key consideration, constraint, and risk in the use and expansion of nuclear energy as a climate mitigation strategy. Nuclear power is relatively water intensive, and the construction, design, and management systems used affect the level of water use and the risks posed to water systems. There are many guidance materials on water management for nuclear operations. Assessments of water requirements and impacts on existing and new nuclear plant construction in mitigation strategies should be required and regulated. Precautions to separate water from reactors are needed in some systems and tight regulations are needed to prevent radioactivity from entering water sources.

Box 7.5. Water use in thermo-electric plants

Thermo-electric power plants generate electricity by boiling water into steam to power a steam turbine. Following this process, the exhaust steam must be cooled and then heated again. The cooling process can be wet (with water), dry (with air), or a hybrid (a combination of water and air). Van Vliet et al. (2016) estimated that over 80 per cent of global electricity generation came from thermal power plants.

When planning and developing plants requiring large volumes of water for cooling processes, availability and impact on water resources must be considered. Thermal pollution (e.g., sudden discharge of warm or cold water into water bodies) harms water quality and ecosystem health. Fish and other wildlife can also be killed when water is taken in from such natural sources as rivers and lakes (USC 2014). Worldwide, it is estimated that one third to one half of existing thermal power plants are located in areas of high water stress (IEA 2021g; Kressig et al. 2018). Multiple cases of power outages or reduced power generation capacity of thermal plants have been recorded in recent years and are regularly reported in mainstream media across all continents.

The water demand and impacts for thermal electricity generation vary slightly between coal, natural gas, nuclear, concentrated solar, and biomass powered plants (Jin et al. 2019). The type of cooling system used has the greatest impact on total water demand. Power plants with once-through cooling systems withdraw high volumes of water, and those that use steam turbines are even more water intensive. Adding recirculating cooling systems decreases water withdrawals and reduces vulnerability to potential constrained access to water. Dry cooling systems use air instead of water and remove water demands but are much less common due to their high cost. In the USA, for example, dry or hybrid cooling systems account for only 3 per cent of thermal generation plants (US EIA 2018) and are not viable for nuclear power plants. Ensuring the availability of cooling water for thermal energy generation under climate change is a key issue for the current and future resilience of energy services (IEA 2018). Beyond climate impacts on overall water availability, global warming impacts may also slightly increase cooling requirements for power plants (Yalew et al. 2020).

7.6 Solar and wind power

7.6.1 Mitigation potential

Solar power, along with wind, is the fastest growing renewable energy source, with continued exponential growth projected in all pathways to achieving the Paris Agreement targets. Current annual solar power electricity production is 582 GW, with annual added capacity per year exceeding 20 per cent growth. Global installed wind power in 2020 reached 743 GW, with an annual growth of 93 GW (GWEC 2021). Solar power accounted for 2 per cent of global gross electricity production in 2018 (IEA 2020b), and wind power is the fifth largest energy source contributing to electricity generation. It accounts for about 5 per cent of total global electricity generation (IEA 2020b), and 15 per cent of the total in Europe.

In nearly every projected pathway (see e.g IPCC 2022, IEA 2021g, and IRENA 2020) the expansion of solar and wind power to replace fossil fuel energy sources will provide the largest reduction in GHG emissions within the energy sector. IPCC (2022) projects solar and wind power as having the highest potential emissions reduction and cost-saving potential of all energy options. Solar PV and wind power each accounted for one third of the overall growth of low-emission energy sources in 2020 (IEA 2021f). Wind and solar power are also the primary technologies already on the market (and not in demonstration or prototype stages). In the IEA main case outlook for renewable energy growth between 2020 and 2025 (IEA 2021f), wind and solar power capacity will double, increasing by over 1,100 GW within 50 years. One key factor in this growth is a projection for solar PV utility generation costs to decrease significantly (by 36 per cent), making it a low-cost option in most countries (IEA 2021f). Still, considerably greater expansion is needed in annual capacity additions, from 134 GW in 2020 to 630 GW in 2030, as predicted in the IEA scenario for net zero emissions by 2050 (IEA 2021g). Record growth in 2020 and the expected increase in capacity additions in upcoming years will not be sufficient to ensure net zero levels.

The Global Wind Energy Council (GWEC) projects additional wind power installation of 469 GW based on its analysis of current pipelines and policy trends as well as continued reductions in costs, improved operations and maintenance, and reduced investor risk (GWEC 2021). Across most net zero scenarios towards the Paris Agreement targets, wind power increases from its current 6 per cent of global energy generation to over 30 per cent (GWEC 2021; IRENA 2020; IEA 2021g). IRENA projects wind power growth under current policy paths to reach 2,037 GW by 2030 and 4,474 GW by 2050. It also shows that to reach the Paris Agreement targets, even larger growth is needed of 3,227 GW by 2030 and 8,828 GW by 2050 (IRENA 2020).

Solar power is projected to expand even faster and to extend further than wind. Under current policy scenarios, IRENA (2020) estimated electricity production from solar PV to increase from 624 GW in 2020 to 1,455 GW by 2030 and 2,434 GW by 2050. To meet emission targets in the IRENA net zero by 2050 scenario, this rate would need to nearly double to reach over 2,500 GW in the next decade and more than 6,000 GW by 2050 (IRENA 2020).

7.6.2 Geographical distribution

Regions in lower latitudes and arid climates generally have higher natural potential for solar power. The World Bank Group, Energy Sector Management Assistance Program (ESMAP), and Solargis have produced the Global Solar Atlas, which evaluates regional solar power potentials. This shows the highest theoretical potential is located in Africa, Central America, the Middle East, and South America, with good potential also in South Australia, Southeast Asia, parts of Southern Europe, and the south-eastern United States. Currently, the largest and fastest-growing solar power producing country is China. Growth is seen worldwide, with the next largest producers in Brazil, Europe, and the USA (Figure 7.5.).

Wind power harnesses air currents to propel turbines that turn electric generators. A collection of turbines located together creates a wind farm, which needs to connect to a power network. Wind farms can be located onshore or offshore, the latter generally having higher capacity but also higher costs for construction and maintenance.

7.6.3 Water dependence and impacts

The transition to solar PV and wind technologies from other more water-intensive energy sources may provide an opportunity to reduce water use from the energy sector, and is often stated as a water-saving measure (GWEC 2021; US Department of Energy 2017).

All solar power technologies require small amounts of water for cleaning PV panels and other collection and reflection surfaces (Ali and Kumar 2017). Water resource requirements for production of solar PV cells,

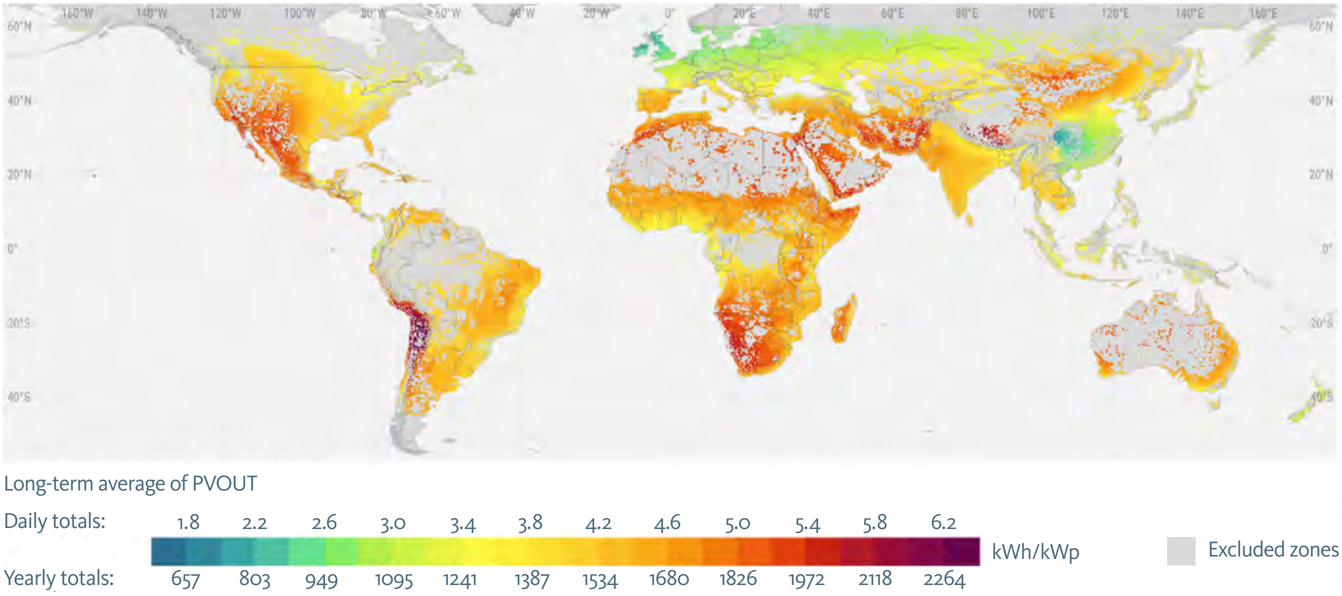

Figure 7.5. Global Solar Atlas projection of solar generation potential by region. Source: ESMAP (2020). Global Photovoltaic Power Potential by Country. Washington, DC: World Bank.

and construction of power plants where used, may need to be considered as they can impact water sources at the site of their production (Jin et al. 2019). Lohrmann et al. (2019) estimated that solar PV technologies require between 2 and 15 per cent of the total water per unit of energy produced compared with nuclear and coal thermal power plants. Production of crystalline silicon PV panels, however, can be relatively water and energy intensive to manufacture (Meldrum et al. 2013). The highest requirements for water from solar power occur in concentrated solar thermal power plants, where water use is similar to that of other thermal power production processes (Jin et al. 2019). Wet processes are most common (due to price and efficiency) for CSP plants, but are water intensive, generally requiring more than 2,000 litres per megawatt hour (Solar Energy Industries Association n.d.). Some solar thermal systems may also contribute to thermal pollution and may use potentially hazardous fluids to transfer heat, which if leaked are harmful to ecosystems (US EIA 2020).

The direct operations of wind power plants require relatively little water (Ali and Kumar 2017). Jin et al. (2019) found the median water requirement for wind power was 43 litres per kilowatt hour, which was the lowest water demand of all reviewed energy sources. Magnets made with rare-earth minerals have significant advantages for enhancing efficiency and lowering costs of turbine operations and are used in more than 75 per cent of offshore wind power globally (Alves Dias et al. 2020). Mining for rare-earth minerals used for magnets in wind turbines can, however, have significant environmental impacts, including on freshwater ecotoxicity and, in some cases, can contribute to eutrophication and acidification (Elshkaki 2021).

7.6.4 Co-benefits and trade-offs

There are several potential economic, health, and environmental co-benefits to the expansion of solar and wind power. Wind and solar PV are the most feasible energy options with the lowest requirement for and impact on water resources. They are thus critically important components of the energy mix to lower pressure on freshwater ecosystems. Wind and solar power also generate less air pollution than fossil fuel sources. Expanded investment in wind and solar PV is currently driving economic growth and employment, with nearly five million people employed in solar power industries and 1.25 million in wind power in 2020. Under clean energy transition scenarios to meet the target to limit global warming to 1.5°C, IRENA projects future employment of 20 million people in solar and more than 5 million in wind power industries by 2050 (IRENA 2021).

There are also several trade-offs and challenges concerned with reducing the negative impacts. Materials and production processes to construct solar panels require significant energy, and can have implications on water, land, and emissions (Elshkaki 2021). Emissions from copper processing, silicon refinement, and chemicals used in the production of solar panels can create toxicity and have negative impacts on human health (Giurco et al. 2019). Expansion of solar PV and wind power also increases requirements for electricity storage and batteries, creating a large increase in the demand for minerals, including aluminium, cadmium, cobalt, copper, gallium, graphite, indium, iron, lead, lithium, manganese, nickel, silica, silver, tellurium, tin, and zinc (Elshkaki 2019; Giurco et al. 2019). Stable supplies and mining of these materials used widely in clean energy technologies can also depend on the availability of high-quality water resources.

Magnets for wind turbines can also significantly increase demand for rare earth minerals, requiring up to two tons for large direct drive turbines. Mining of these materials can lead to numerous negative impacts on environment, health, equity, and human rights, as well as impacts on water quality and scarcity (Mancini and Sala 2018). Impacts can include poor worker safety; conflict over land rights; labour rights violations; air, soil, and water pollution; and biodiversity loss (Corneau 2018).

7.6.5 Potential implications for governance

Expansion of solar and wind power, and efficiency improvements account for meeting as much as 50 per cent of energy demand by 2050 in several scenarios to meet the Paris Agreement targets. If these are not reached, there is likely to be greater demand and pressure placed on water resources from all other alternatives. While solar PV is less water intensive than alternatives, CSP may require significant water resources for cooling, and life-cycle requirements for raw materials to produce solar panels must be understood so they can be sourced sustainably.

Hybrid power plant at Palm Springs, California, with solar PV and wind turbines. Source: Shutterstock.

Solutions for energy storage and flexibility are critical to enable energy systems that are reliant on variable energy sources such as wind and solar PV. Water implications of those solutions can be large. Most current energy storage solutions are provided by pumped hydropower, which has greater capacity for energy storage for longer periods of time than batteries (see section 7.2). There are potential solutions for pumped hydropower that use closed-loop systems between existing reservoirs that avoid impacts to larger river systems. Expansion of mining of minerals (e.g., cobalt, copper, graphite, lithium, silicon), as well as rare earth materials used in the construction of batteries, fuel cells, grids, magnets, and solar cells will also require stringent oversight and serious investment to prevent contamination of surface- and ground-water sources, as well as negative impacts on human and environmental health (Elshkaki 2021). OECD (2019) cited impact areas for risk mitigation to include accidents endangering works, dam failures, exposure to hazardous substances, and air pollution, as well as land and water pollution. It also notes many countries with rich mineral resources lack regulatory structures and capacity for risk mitigation in these areas as well as data and oversight of risks and environmental impacts of mineral mining across the supply chain.

Distributed solar PV and wind power are variable energy sources and can require investments and measures to improve overall power system flexibility and grid infrastructure (IEA 2021g). This flexibility can be provided by hydropower, geothermal or nuclear power. Each of these options, as discussed in this chapter, requires effective management to reduce water risks and impacts.

7.7 Conclusion and outlook of water, climate and energy production

Fossil fuel energy production requires significant water resources. Roughly 70 per cent of the water used by the energy sector, excluding hydropower goes to the production of fossil fuels and thermal power generation plants (IEA 2018). Total water withdrawals and consumption will need to be reduced significantly to reach the SDG targets with available resources.

The transition to renewable energies can provide opportunities to reduce pressure and impacts on water sources from the energy sector. The variation in the demand and pressure placed on water sources can vary dramatically depending on the future energy mix and its water management. There is a risk that renewable energy production will increase demand and pressure on water, as well as potential water risks that could constrain some options for renewable energy development in different regions. Low-emission energy generation that requires the operation of thermal power plants (geothermal, CSP, nuclear) are highly dependent on water and must be managed to ensure access and impacts on water sources are sustainable. Potential impacts and constraints on water sources are also critical to consider for the type and amount of bioenergy and hydropower involved in mitigation strategies.

Scenarios for future energy use that meet zero emission targets by 2050 (IEA 2021g; IRENA 2020; Rogelj et al. 2018) place the lion's share of the transition on expanding solar and wind power and making huge strides in energy efficiency and demand management. They are also heavily dependent on the uptake of technological innovations that are still in demonstration or prototype stages, including BECCS and green hydrogen (IEA 2021f). Similarly, clean energy transitions can have positive impacts on human and environmental health as reduction in burning of fossil fuels will lessen air pollution and toxic leaching from coal mines (Luderer et al. 2019). However, nuclear, hydropower, geothermal, bioenergy, solar, and wind power production are not free from side effects or dependencies, which should be weighted in assessments and investments in energy production. For example, ecosystem impacts from land-use changes required for the development of fuels, electricity generation, and the electricity grid need to be taken into account (Luderer et al. 2019). These assessments can also point to better solutions, for example, through closed-loop pumped hydropower systems to provide energy storage as part of solar and wind power networks.

Most projections for the energy transition also speculate on the expansion of green hydrogen, converters, and electric transport to fulfil and reduce the need for carbon fuels. Access and proximity to water is a fundamental requirement for hydrogen, which would mean that conversion of solar or wind power to hydrogen cells also needs to be located near and use water sources. Most pathways of electrification of transport project massive upscaling of battery production (IEA 2021g; IRENA 2020). Non-fossil mineral depletion, and impacts from its mining and extraction, pose risks for environmental damage and constraints to development, particularly for energy storage, as well as for nuclear, solar, and wind power. If solar or wind power are constrained, there may be significant implications for water resources and ecosystems as alternatives such as nuclear, geothermal, hydropower, and bioenergy can have higher overall impacts on water, and environmental and human health. Moreover, the demands and/or impacts on water sources for hydropower, bioenergy, nuclear, and geothermal may limit their sustainable expansion, where risks to ecosystems, biodiversity, and human health and security need to be considered. There are also additional water risks that will require more regular and comprehensive assessment to ensure clean energy transition, particularly with the production of fuels for transport and heating.

Access to energy in the future is projected to expand worldwide. There are an estimated 768 million people without access to electricity, and as many as half of the people in the world live in places that do not have access to sufficient electricity to fulfil basic development needs (IEA 2021d). Many regions must balance high water stress, population growth, economic development, and expansion of energy access (Oki and Quiocho 2020). While providing basic electrification adds relatively little to total energy demand, expanding energy generation in water-stressed regions will be an essential, unavoidable challenge to face, and must consider potential trade-offs with other demands for water resources that will follow national development.

Thus, in all energy planning, in both projected and known developments, water is an essential element that must be integrated across all aspects of development. This must be done while the transformation to clean and renewable energies is accelerated. The decline in economic activity and travel following the Coronavirus 2019 pandemic led to a 5.8 per cent reduction in emissions from the energy sector in 2020, which is the largest in modern history by a considerable margin (IEA 2021c). In 2021, however, global energy-related CO_2 emissions were estimated to rise by 1.2 billion tons, the second-largest annual increase in CO_2 emissions in history. This was due largely to a rebound in coal and oil use. Strong commitment and at least USD 4 trillion of annual investment in clean energy transitions and infrastructure are needed to change the course again and ensure that emissions trends in the energy sector move in line with achieving net zero targets by 2050 (IEA 2021g). For these investments and commitments to succeed, it is critical to account for linkages between water, energy, and climate security.

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CHAPTER 8

Water risks and win-wins for climate mitigation

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Chapter 8 Contents

Wind turbines in the Gaomei Wetlands, which spans over 300 hectares close to Taichung City, Taiwan. Source: Shutterstock.

Highlights

- Water-wise climate mitigation plans across national and local levels must identify, assess, and incorporate water risks as well as win-win opportunities for water-related mitigation measures.
- **Identifying water risks includes analysis of how water might limit the success of many climate mitigation measures, as well as assessments of where mitigation measures could pose risks to freshwater systems and the water cycle**. Specifically, such analysis requires review of water-related risks in development of different renewable energy options as well as the potential implications of biodiversity loss and ecosystem degradation – which not only reduce carbon sequestration potential of terrestrial and aquatic ecosystem-based mitigation measures but can also lead to emission of greenhouse gases.
- **Utilizing win-win opportunities will be critical to effectively and sustainably reduce emissions through water-wise climate mitigation action**. Highlighted measures include those that can be taken in drinking water and sanitation services as well as actions to protect, restore, and manage terrestrial and aquatic ecosystems (e.g., wetlands, river systems, forests, agriculture).
- Four leverage points are identified, which combined sets an agenda for action to ensure that climate mitigation is resilient, robust, and water-wise: 1) Promote sustainable low-emission water management; 2) Invest in Nature-based Solutions and healthy ecosystems; 3) Navigate water-wise energy pathways; 4) Accelerate transition to circular solutions and sustainable lifestyles.

8.1 Introduction

The sectoral chapters of Part II (Chapters 4–7) in this report give many examples of how freshwater is a key component of solutions to mitigate global warming in ways that are sustainable, resilient, and beneficial. They review key areas for climate mitigation across water, energy, and ecosystems to reveal where they directly depend on, or impact water systems, showing that:

- **Effective climate mitigation measures acknowledge and manage water interdependencies.** Most mitigation measures needed to reach climate neutrality depend on functional freshwater systems and healthy ecosystems. A great majority of mitigation measures worldwide have a link to water management and/or the water cycle in many and diverse ways that must be understood, planned, and accounted for.
- **Uninformed climate mitigation planning generates unintended impacts on water systems and the water cycle.** Most mitigation measures needed to reach climate neutrality also have an impact on freshwater resources. If not planned carefully, negative impacts on ecosystems and freshwater resources might threaten water security adding additional burden on adaptation measures or, in some cases, even leading to increased emissions hindering climate change mitigation. A strong interdependence exists therefore among climate mitigation, water resources management, and water security.
- **Effective management of water resources and water-wise management of land systems and freshwater ecosystems can actively contribute to emission reductions.** Sustainable land, water, and wastewater management, and healthy freshwater ecosystems hold large, untapped greenhouse gas (GHG) mitigation potential and thus, water is a crucial mitigation lever in its own right.

This chapter builds on these findings to identify risks and win-wins for carbon-smart and water-wise climate planning, investment, and implementation. Unmanaged risks could lead to detrimental outcomes, including failure to realize the expected mitigation potential of a measure; negative impacts on freshwater systems and human livelihoods; or even increased emissions caused by disrupted freshwater ecosystems. Section 8.1 identifies mitigation measures where water risks could limit the success of the climate mitigation measures, while section 8.2 reviews mitigation measures that could pose risks to the water cycle. In both these cases of water risks, thorough evaluation is needed to assess, avoid, and minimize potential trade-offs and ensure that the benefits provided by mitigation measures can be sustained and outweigh potential costs and possible negative impacts on water security.

Section 8.3 identifies win-wins where sustainable water management and governance can contribute to reduced GHG emissions. Four priority areas for water-wise climate action are presented. These highlight specific ways freshwater management can contribute directly to climate mitigation and therefore must be included in climate (mitigation) plans and policies. They also showcase areas where mitigation measures can provide co-benefits or do not endanger water security compared to alternative climate mitigation options.

Overall, this chapter closes the knowledge gap concerning the interrelations between the water cycle, freshwater availability, freshwater limitations, and mitigation of GHG emissions. It points to essential opportunities to reduce potential trade-offs, mitigate risks and enable synergies that mitigate climate change, and relieve pressure on freshwater systems.

8.2 Water risks can limit the success of climate mitigation

Mitigation does not work without water. Most mitigation measures needed to reach climate neutrality depend on functional freshwater systems. This report underscores the central role of freshwater as an enabler for climate change mitigation across sectors, showing evidence that as most mitigation activities rely on freshwater access, mitigation targets cannot be met without sufficient freshwater resources and sustainable water management. This section reviews mitigation measures that have been identified throughout this report as being particularly sensitive to constraint by water risks, such as water shortages, floods, or climate-induced changes to the water cycle, unless effective plans are in place for the event of such risks.

8.2.1 Water risks for mitigation measures in freshwater ecosystems

Freshwater ecosystems can function as carbon sinks; however, this is reliant on a healthy water cycle and sustainable water governance. Water scarcity and ecosystem degradation in freshwater systems, caused by climate change and unsustainable land use practices, can instead cause these carbon sinks to release GHGs (Anisha et al. 2020; Paranaíba et al. 2022). As the climate change mitigation potential is essentially connected to water availability, ecosystem conservation and restoration measures to ensure a healthy water cycle are critical for freshwater ecosystem-based mitigation. For instance, between 1970 and 2015, the area of the world's natural inland and coastal wetlands declined by ~35% (Gardner and Finlayson n.d.). About 15 per cent of the world's peatlands have been drained for agriculture, forestry, and grazing, resulting in at least 5 per cent of the total global anthropogenic emissions (Joosten et al. 2012; Tanneberger et al. 2017). A recent study confirmed that increasing water limitation occurs in 73 per cent of global warm land areas, that is, where air temperature >10°C for most of the year (Denissen et al. 2022).

Climate change is already altering ecosystems' water cycling and habitats, which has an impact on their mitigation potential (IPCC 2022), even more so under future climate and environmental changes. Key risks highlighted in this section explain how ecosystems that are subjected to water scarcity, degradation, and pollution, are expected to increase emissions of GHGs.

8.2.2 Water risks for mitigation measures in land systems

Land systems can function as carbon sinks; however, this function is reliant on an intact water cycle and healthy soils. Without freshwater, soils are sensitive to undergoing a shift from storing GHG to becoming a source of emissions. The carbon sequestration potential of soils is impacted by a number of factors including inherent soil texture, temperature, water, and nutrients. Water scarcity is already constraining both soil carbon sequestration and food production potential, not least in regions with rapid population and economic development. For instance, according to FAO SOFA (Gustafson 2020), 40 per cent of rainfed high and low input agriculture and 20 per cent of irrigated agriculture are currently affected by water constraints, and hence productivity is lower than attainable (i.e., there is a water yield gap). Water is a natural limiting factor in food and biomass production in both rainfed and irrigated crop-livestock systems. Climate change, rainfall variability, and freshwater availability and access can be expected to further limit the process of carbon sequestration in soils, as well as in biomass, in highly managed crop, agroforestry, and grassland systems. However, the actual rate of change at regional to local levels has yet to be explored, and different systems will be impacted in divergent ways. Increased rainfall can lead to higher soil erosion rates with loss of soil organic matter, as well as flushing of soil and carbon from wetlands to streams and rivers and result in higher GHG emissions. Planning ecosystem protection, restoration, or management must also consider potential impacts of climate change by implementing measures that can adapt to changing conditions (IPCC 2022).

Similarly, the capacity of forests and grasslands to function as carbon sinks is dependent on freshwater. Drainage, clearcutting, or excessive grazing of ecosystems accelerate emissions of CO_2 and methane, which must be halted. The carbon sink strength in some tropical forests has recently peaked, while in other tropical, subtropical, and temperate forest zones it appears to be slowing down (Hubau et al. 2020). Deforestation, forest degradation, and unsustainable management of tropical forests are likely to cause regional reductions in rainfall, increased frequency and severity of droughts, and teleconnected hydrological and climatic impacts through influences on large-scale atmospheric and oceanic circulation dynamics (Wang-Erlandsson et al. 2017; Lawrence and Vandecar 2015). Deterioration of forest water cycles risks lowering agricultural productivity regionally and globally, causing irreversible damage to biodiversity, and turning the forest carbon sinks into carbon sources.

8.2.3 Water risks for transitioning towards low GHG emission energy sources

Changes in the water cycle have significant implications for hydro- and thermoelectric energy production, which account for some 95 per cent of global electricity generation (IPCC 2022). Hydropower currently provides 16 per cent of total electricity generation and 43 per cent of global electricity from renewables (IEA 2021). There are risks to energy generation by hydropower where there could be a decrease in the volume of water that flows through a plant. This could occur as a result of the effects of climate change and variability, which can cause less rain and more evapotranspiration, or from increased water withdrawals for other uses (such as the domestic, industrial, or agriculture sectors). Therefore, the potential impact of climate change on hydropower generation during the lifecycle operation of the infrastructure and the entire river basin system must be considered to ensure that energy generation of a hydropower plant can be sustained or adjusted under different plausible scenarios. For example, in some cases, dams can support flood protection downstream, but can also pose higher risks for flooding upstream in areas surrounding constructed reservoirs, as well as more devastating flood events occurring if there are dam breakages.

Impact assessment and risk mitigation strategies are needed for hydropower development and operations to reduce negative effects on water balances and freshwater ecosystem functions as well as potential increased emissions from water bodies that result from alterations caused by hydropower installations. For instance, reservoirs created by dams, with fluctuating water tables and a high occurrence of organic material, produce considerably more methane than natural lakes or other surface waters, and it is asserted that newly formed hydroelectric reservoirs emit between 3 and 10 times more GHG than natural lakes of the same size (Prairie et al. 2021; Fearnside 2006; Tremblay et al. 2005). The depth, age of the utrientrs, temperature, pH, and availability of utrientts in these waters and their catchments all influence GHG emissions. Accounting for downstream impacts is particularly important in transboundary basins together with processes for risk mitigation and benefit sharing.

Freshwater is also vital in the context of thermoelectric plants for nuclear, concentrated solar power, and geothermal energy. When planning and developing such plants requiring large volumes of water for cooling processes, the availability and impact upon water resources must be considered. Thermoelectric plants generate 80 per cent of the current electricity worldwide, primarily with coal and gas power. They are also used in nuclear, concentrated solar, and biomass plants, where those energy sources heat water to power a steam turbine and generate electricity. Water is also required for cooling in the vast majority of plants, and some geothermal power plants use water for cooling and re-injection rather than geothermal liquids (Jin et al. 2019). Many thermal power plants are currently located in areas under high water stress, with estimates ranging from 33 per cent (IEA 2021) to 50 per cent (Kressig et al. 2018). Water shortages and droughts can lead to either disruptions or reduction of energy generation, as seen in Europe, India, and the United States in the past decade, or heightened competition for water use in other sectors (Ahmad 2021). From 1981 to 2010, electricity production from thermoelectric plants decreased by 3.8 per cent in places experiencing droughts (IPCC 2022). Incomplete information on water use by thermal power plants (both existing and planned) in many regions can further increase risk for disruptions of electricity generation or unsustainable withdrawals of water (van Vliet et al. 2016). For example, once-through wet cooling processes withdraw high volumes of water, which could be reduced, where feasible, by use of recirculating water systems, and dry cooling systems.

Access to freshwater is also critical for Bioenergy with Carbon Capture and Storage (BECCS). Potential land constraints and requirements for water are key determinants to potential investment in BECCS in different locations around the world. BECCS has a certain theoretical potential to provide energy and increase carbon sequestration, leading to climate-positive results (where more carbon is removed than emitted for energy production). However, the IPCC showed in its 1.5°C compatible pathways that scenarios in which emissions reductions occurred required large expansion of BECCS to capture more released carbon (IPCC 2018). Projected freshwater use for mitigation appears to be particularly high for potentially irrigated biomass plantations dedicated to BECCS (see Chapter 7). Current and projected freshwater use in other sectors must be considered to evaluate feasible and sustainable expansion of BECCS. Figure 8.1 illustrates that the freshwater withdrawals required for BECCS may reach as much as, or more than, those in other sectors (agriculture, household, and industrial use). This could occur if BECCS is developed to reach a very high level of energy production and carbon sequestration and expanded beyond rainfed areas onto lands worthy of protection (Stenzel et al. 2019, 2021).

Achieving this maximum BECCS scenario would also place bioenergy as the largest water user in many regions (Figure 8.2). Such large-scale expansion could push total global human water consumption beyond the freshwater planetary boundary, suggested to be 4,000 $km^3\ yr^{-1}$ or even significantly lower (Gerten et al. 2013; Steffen et al. 2015). Accordingly, large-scale BECCS has been found to be incompatible with the freshwater boundary and also with other planetary boundaries such as those for land system change, biosphere integrity, and nitrogen cycling (Heck et al. 2018). Thus, such efforts to mitigate the transgression of a planetary boundary for climate change (broadly equivalent with the 1.5°C

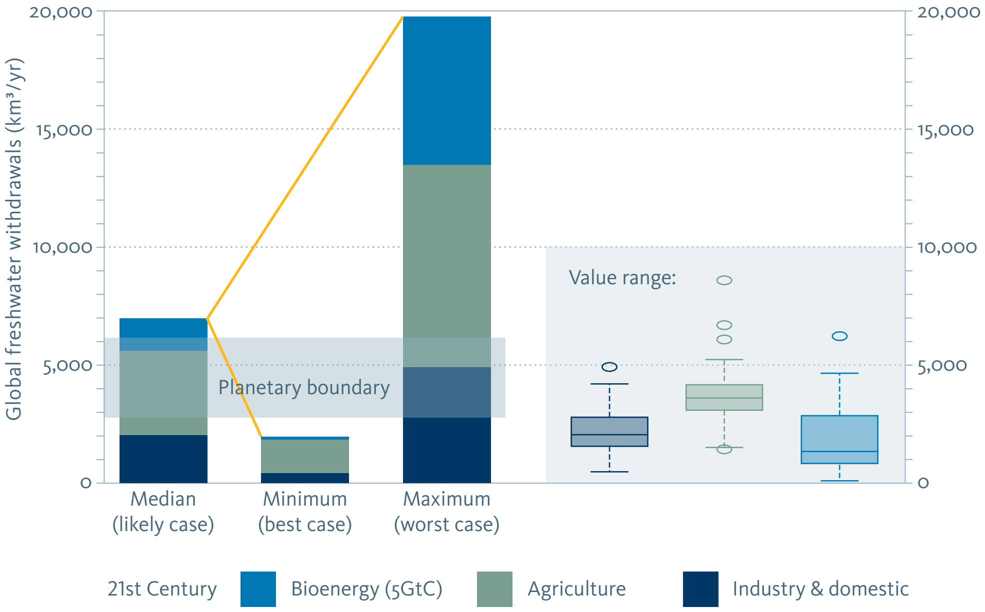

Figure 8.1. End-of-century projections of annual blue water withdrawals for bioenergy, agriculture, and industries plus households. Data from references in Stenzel et al. (Stenzel et al. 2021); water use for irrigation of biomass plantations normalized to negative emissions of 5 GtC. A) median value for each sector, b) uncertainty ranges for each sector according to study and scenario differences.

target) might severely compromise the status of other boundaries, which emphasizes that benefits and side-effects of mitigation need to be evaluated in a broader Earth system context (not solely focused on climate and water). These interactions and trade-offs require robust and integrated assessments, including identification of synergistic solutions. Such analyses also need to explicitly incorporate the multiple potential trade-offs regarding freshwater. This is particularly important as the uncertainty about sector-specific freshwater demands and possible intersectoral competition is very high. Scenarios of potential future water use that integrate the bioenergy sector with the agricultural, industrial, and domestic sectors are needed to highlight the potential scale of risks but are not yet available (Figure 8.2).

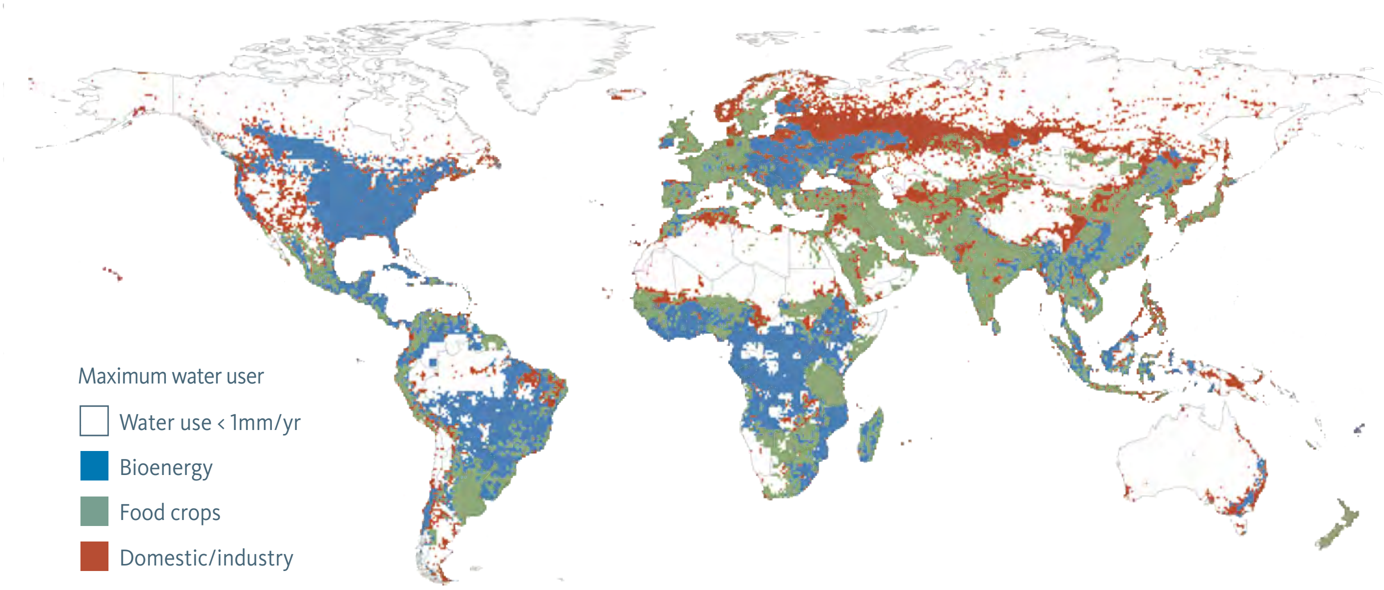

Figure 8.2. The global map indicates regions (blue colour) where bioenergy would use more freshwater than other crop production or domestic and industrial use. Dominant water use sector per 0.5° grid cell calculated from average annual water withdrawals for irrigation of agricultural crops, irrigation of BECCS biomass plantations, and households/industry purposes, respectively, for the period 2090–2099 under the HadGEM2-ES RCP2.6 climate and SSP2 socio-economic scenario of the ISIMIP2b model ensemble also analysed in Stenzel et al. 2021.

8.3 Mitigation measures can pose risks to the water cycle

Water must be protected from uninformed mitigation planning. Most mitigation measures needed to reach climate neutrality also have an impact on freshwater resources. If not planned carefully, negative impacts on freshwater resources might threaten water security adding additional burden to adaptation measures or, in some cases, even leading to increased emissions hindering climate change mitigation. This section reviews mitigation measures that have been identified throughout this report as running a particularly high risk of posing potential harm on freshwater ecosystems.

8.3.1 Risks to the water cycle posed by ecosystem-based mitigation measures

Misguided implementation of land systems climate mitigation measures can cause local water shortage, biodiversity loss, and harm to local communities. Chapter 6 outlined how mitigation measures and Nature-based Solutions (NbS) in land systems in general have a positive impact on the water cycle, but there are a few examples where action to mitigate climate change may risk disrupting water flows and reduce freshwater availability. Measures where trees are planted, such as in forest restoration, afforestation, reforestation, and agroforestry, risk incurring a high demand for freshwater and having negative impacts on river flows and groundwater, particularly in dry areas and during dry periods (Wang et al. 2020; McVicar et al. 2007; Mu et al. 2007). For instance, a study analysing reported change in annual water yield in forest restoration and other forms of forest cover expansion, showed that the yield decreased in 80 per cent of the cases, while in 6 per cent the effect was positive (Filoso et al. 2017). To minimize these negative effects, it is important to make water-wise plans for which tree species to plant and at what densities, for instance by promoting tree species that consume less water and/or are more effective at improving soil hydrological functioning (Scott and Prinsloo 2008; Ferraz et al. 2013) or by ensuring long rotation periods.

Species selection is also of high importance in agricultural lands for climate mitigation measures to sustainably manage soils, croplands, or grazing lands, especially in arid and semiarid regions. One option is to avoid planting species that are sensitive to water stress or have high demand for water, in favour of more resilient species. In situations where more water-demanding species are needed, there are sustainable management options that can reduce water risks in terms of agroforestry and other climate-smart integrated farming systems, such as use of shade crops, crop rotations, cover crops, and integrated crop-livestock systems (Kakamoukas et al. 2021; Niggli et al. 2009). Technical measures to improve water use efficiency can also be used, such as micro- or drip-irrigation (Parthasarathi et al., 2021).

8.3.2 Risks to the water cycle posed by energy systems mitigation measures

The transition away from high-emission fossil-based energy sources lies at the centre of all efforts to reach climate mitigation targets that can limit planetary warming to 1.5°C. Here, actions to mitigate risks posed to freshwater systems resulting from energy generation is critical. Chapter 7 outlined the many ways water is used for generation of low-emission energy from hydropower, bioenergy, nuclear, geothermal, solar, and wind power. In relevant cases, water risks should be evaluated and managed in line with the local conditions and in ways that are resilient under climate uncertainty. However, without proper planning, the transition towards renewable energy sources could pose significant risks to freshwater systems.

For example, thermal pollution (e.g., sudden discharge of warm or cold water into water bodies) harms water quality and ecosystem health. Fish and other wildlife can also be killed when water is abstracted from a river or lake. Some solar thermal systems may also use potentially hazardous fluids to transfer heat, which if leaked are harmful to ecosystems (US EIA 2020). In geothermal power development, measures are also needed to prevent contamination of groundwater with drilling fluids (during the drilling process), depletion, and warming of groundwater during the mass withdrawal operations, and contamination of groundwater and surface water ways in the disposal of waste liquids (from both surface disposal and reinjection processes) (Sayed et al. 2021). Accidents or failures at nuclear plants (such as the Fukushima Daiichi Nuclear Power Plant disaster of March 2011) can also pose harmful risks to ecosystems and human health that potentially last for decades (Lu et al. 2021).

8.4 Win-wins for high-potential mitigation opportunities

This section highlights four key ‘leverage points’ to ensure water and climate security. Leverage points are areas where actions can have great positive impacts on complex systems to achieve transformative changes (Fischer and Riechers 2019). They also cover critical areas for mitigation that have either positive co-benefits or reduce impact on water sources compared to alternative options. Actions in these areas include climate mitigation measures where the use, protection, or management of freshwater directly results in reduction of emissions. Such measures are recommended to be explicitly included in a climate mitigation planning process and implementation.

1. Promote sustainable low-emission water management
2. Invest in Nature-based Solutions and healthy ecosystems
3. Navigate water-wise energy pathways
4. Accelerate transition to circular solutions and sustainable lifestyles

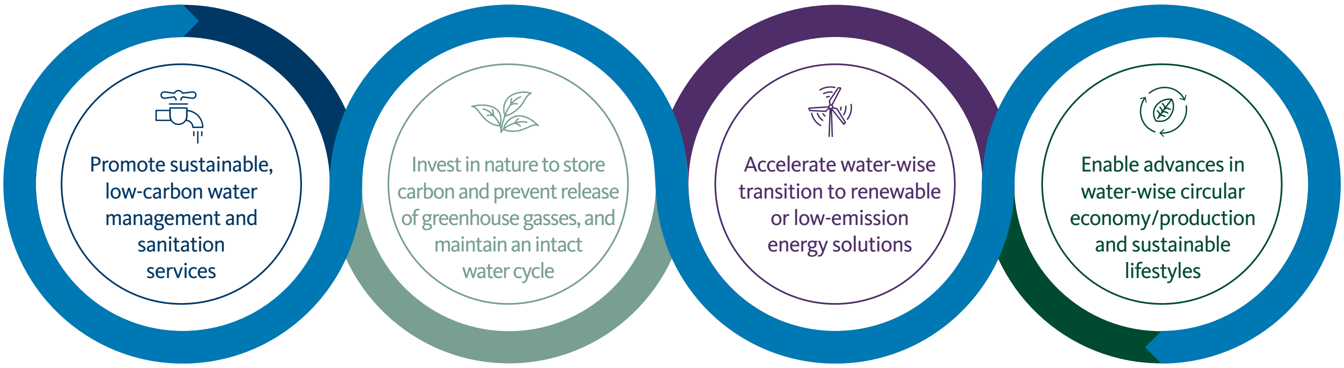

Figure 8.3. Key leverage points in climate mitigation to ensure water and climate security, ensuring a resilient, robust, flexible, and water-wise transition. Source: SIWI.

The first three leverage points are cross-cutting opportunities that are identified across the mitigation areas analysed in Part II, and which directly link to water. The final one covers issues beyond those covered in the report, but which have clear positive impacts on water, climate mitigation, and sustainable development. For each leverage point, recommended priority areas for action are provided.

8.4.1 Promote sustainable low-emission water management

This report has shown how the protection and sustainable management of freshwater in many cases can contribute to climate mitigation. Sustainable water management may help improve climate mitigation in water and sanitation services (Chapter 4); protect, manage, and restore freshwater and terrestrial ecosystems that store carbon (Chapters 5 and 6); and secure energy generation to limit potential harmful impacts (Chapter 7). For example, increased water productivity and sustainable practices can contribute to potential cultivation of BECCS that can be done without causing resource shortages.

1. Action: Reduce emissions and recover energy in drinking water and sanitation services

There is great potential to reduce or avoid GHG emissions while improving and extending wastewater collection and treatment, and safe sanitation for all people worldwide. Chapter 4 of this report detailed how improved water, wastewater, and sanitation management is a major opportunity for climate mitigation. A number of measures could be taken to reduce emissions from water supply and treatment networks, including optimized process selection and operations of wastewater and faecal sludge treatment and discharge as well as enhanced wastewater collection and treatment (including decentralized sanitation solutions). There is potential also for energy efficiency measures, increased use of renewable energy for water processes, as well as reducing demand for, and losses of, water. Reuse of greywater could also reduce energy demands and provide multiple benefits for climate resilience. There is also an enormous opportunity to transform wastewater and sludge into sources of low-emission energy and heat (IWA 2022). This energy generation potential could reduce the need for external energy inputs, perhaps even generating more energy than needed for water supply and sanitation services. Selling this low-emission electricity, heat, and biogas to others to replace fossil energy sources could help water and sanitation services both recover costs for treatment and achieve net-zero emissions (IEA 2018). Overall, to fully account for and report these activities as mitigation actions, it is critical to measure emissions from water and sanitation services as well as their reductions.

There is a need to identify areas where climate finance can provide incentive and capacity to reduce or prevent emissions in the provision of basic and advanced sanitation solutions. A large share of the wastewater and faecal sludge generated in low-income countries remain untreated or partially treated, which results in pollution of water bodies and uncontrolled release of nitrous oxide and methane gases through biodegradation of organic matter. Currently, 2 billion people lack access to basic, safe sanitation services and an additional 2 billion people will join the global population by mid-century (UN-DESA 2022). The extension of wastewater collection and treatment systems in all areas, including decentralized solutions, is essential for achieving the Sustainable Development Goals (SDGs). Some options can potentially lead to lower emissions, while certain treatment processes instead lead to increased emissions (SuSanna 2022). Water Sanitation and Hygiene (WASH) actors could also engage more actively in assessing climate risks and vulnerabilities that affect services provision, report GHG emissions from water and sanitation systems, and calculate reductions made of those emissions where possible. This could serve as a basis to promote WASH interventions that better integrate the mitigation potential in addition to serving as adaptation solutions. Project experience has created strong knowledge, guidance, technologies, and interventions for energy-efficient and low-climate-impact water and wastewater processes that can be scaled up through investment, capacity-building, and training using climate financing. Tools for measuring and reporting GHG emissions from water and sanitation systems to national GHG inventories have been developed and are available for use (Kerres et al. 2022). More and better efforts are needed, however, to secure adequate capacities of WASH stakeholders, at all levels. As a first step to strengthen WASH in the climate agenda, vulnerability and climate risks linked to the delivery of WASH services must be identified and assessed, particularly documenting GHG emissions from water and sanitation systems. Available knowledge and evidence need to inform climate policies, strategies, and the formulation of the response and related plans, that is, promoting WASH interventions that not only consider adaptation solutions but also better integrate the mitigation potential.

2. Action: Adopt watershed-scale emission reduction strategies

Emission reduction goals need to be given greater emphasis in broad water resources management strategies. Although wetlands and peatlands are often included in national climate policies (e.g., Nationally Determined Contributions, (NDCs), other freshwater systems, such as rivers, lakes, and reservoirs are still not commonly included. Freshwater systems in many places have been altered and risk becoming net sources of emissions. While there is evidence that rivers are emitting GHG, knowledge on the drivers of emission, the patterns and variability is incomplete due to a relatively small number of observations scattered around the world with varying measurement techniques used. Data on emission and sequestration patterns for rivers and streams are often absent, and these are sorely needed. It is important to facilitate development of measurement technologies that can be used to acquire standardized datasets worldwide, targeting long-term, continuous, large-scale data that can be measured simply and at low cost.

GHG production in aquatic systems is fuelled by inputs from the watershed (Li et al. 2021). Land use, pollution, human activities, hydrological regime, changing climate, etc., can influence the emissions of wetlands, freshwater lakes, streams, and rivers, and estuarine, coastal, and marine systems. Effective emission reduction strategies entail coordinated approaches for land management, restricting nutrient loading, maintaining and improving ecohydrological connections (see, e.g., landscape approaches detailed in Chapter 9). Watershed-scale soil erosion control and nutrient reductions may help reduce GHG emission from lakes and reservoirs. Additional measures that can contribute to GHG emission reduction include connecting rivers to floodplains, limiting channel alterations, and improved context-specific monitoring systems. There also need to be financing mechanisms and tools in place to monitor and reduce emissions from freshwater systems and blue carbon ecosystem management at the local, regional, and national levels. Capacity-building and other forms of support, including better data on aquatic environments, may be needed to materialize implementation.

8.4.2 Invest in Nature-based Solutions and healthy ecosystems

Human activities in agriculture, forestry, and other land use (AFOLU) account for 22 per cent of the net anthropogenic GHG emissions (Shukla et al. 2019). In addition, so-called negative emissions (net CO_2 removals) from ecosystems are part of all IPCC scenarios that limit global warming to +1.5°C (IPCC 2018). Over 90 per cent of AFOLU emissions result from agricultural practices, where IPCC has estimated a mitigation potential of 4.1 $GtCO_2$-eq yr^{-1} through measures taken across the sector over the next three decades (IPCC 2022). Beyond reducing emissions from agriculture, the capacity of ecosystems to absorb and store carbon is an essential component in those scenarios. Expanded and improved management of protected areas is critical moving forward. IPCC (2022) evaluated that 30–50 per cent of the planet's land, freshwater, and marine areas must be protected to sustain biodiversity and needed ecosystem services. This is significantly more than exists currently, where only 15 per cent of land, 21 per cent of freshwater, and 8 per cent of marine areas are in protected zones. IPCC (2022) assessed measures involving the protection, management, and restoration of forests, peatlands, coastal wetlands, savannas, grasslands, and other natural ecosystems to reduce emissions and/or sequester 7.3 $GtCO_2$-eq yr^{-1}, which represents the greatest climate mitigation potential in the AFOLU sector.

The ability of land-based ecosystems to adapt to a changing climate is defined by the availability and variability of freshwater (Boltz et al. 2019). The mitigation potential of ecosystems and NbS is limited in terms of adapting to increased global warming, in that mitigation potential will gradually be reduced with increased global warming. There is evidence that hydrological changes are already pushing some ecosystems and ecological processes towards irreversibility, such as retreating glaciers or tropical forests shifting into savannas. Also, it is important to note that ecosystem carbon sinks and storage only can be a complement to carbon reduction efforts in other sectors, such as in transport and industries.

Chapters 5 and 6 of this report showcased how healthy ecosystems – and thus a healthy water cycle – contribute to enhancing climate change mitigation potential by sequestering carbon below and above ground, while also safeguarding freshwater resources, protecting biodiversity, and ensuring sustainable and resilient livelihoods. Managing ecosystems to protect carbon stocks in biomass and soil can have immediate climate mitigation benefits but the stored carbon is vulnerable to drought and increased temperatures (Seidl et al. 2017; Bastin et al. 2019). In addition, ecosystem management interventions need to be put in a local context to be effective as the outcomes are dependent on, for example, elevation and topography, species composition, climatic zone, and level of degradation.

Further, this report examined the role of freshwater linked to measures in terrestrial and freshwater ecosystems, including wetlands, lakes, and rivers as well as freshwater-dependent coastal and marine systems (Chapter 5), forests and agricultural systems (Chapter 6). It shows how NbS for climate mitigation involve measures of protecting, restoring, and better managing the natural capacity of ecosystems to absorb and store atmospheric carbon, and how healthy water cycles are necessary to achieve full mitigation potential and ensure that the stored carbon is not released into the atmosphere.

1. Action: Invest to protect, restore, and maintain wetlands, peatland, and forests

Conserving wetlands, peatlands, and all blue carbon ecosystems is critical to avoid drainage and other anthropogenic pressures creating net sources of GHGs. With more than 75 per cent of Earth's land areas being substantially degraded (Kotiaho et al. 2018), it is essential to restore ecosystem functions and services for climate change mitigation. Freshwater and healthy water cycles are necessary for the ability of ecosystems to provide services, including carbon storage and sequestration in vegetation and soils. Healthy and well-managed ecosystems are key. For instance, wetlands store more than 30 per cent of the estimated global carbon emissions (Nahlik and Fennessy 2016) on about 7 per cent of the world's surface (Ramsar Convention on Wetlands 2018; Mitsch and Gosselink 2015), and peatlands, despite covering only 3 per cent of the global land surface, can store about 21 per cent of the global total soil organic carbon stock (IPCC 2022).

Investigating how polluted and altered water bodies lead to more GHG emissions is critical to understand how different rivers across the world contribute to GHG emissions, and how these can be mitigated. Rivers that drain watersheds in forested, urban, and agricultural landscapes result in different riverine dissolved GHG concentrations and fluxes, depending on the level of ecosystem degradation in the catchment area. Nutrient pollution makes most rivers in the world supersaturated with GHG. Still, very few studies have assessed concentrations of the three GHGs (CO_2, methane, and nitrous oxide) together in a river system and there is no consistent evidence showing the roles of specific river types in contributing GHG emissions. GHG emission assessments need to incorporate multi-year monitoring designs to account for temporal variability in environmental conditions that affect GHG fluxes. Fluctuating surface-groundwater tables in reservoirs, lakes, peatlands, and other lentic waters is another particular source of GHG emission that needs to be managed efficiently to reduce risks to climate change mitigation. For instance, reservoirs created by dams, with fluctuating water tables and a high occurrence of organic material, produce considerably more methane

The extensive peatlands of West Papua, Indonesia. Land clearance in peatland areas is now prohibited in Indonesia and there are ongoing projects to restore degraded peatlands across Papua. Source: Shutterstock.

than natural lakes or other surface waters. Worryingly, methane emissions and global warming reinforce each other in a vicious cycle. Higher water temperatures favour methane emissions (Zhu et al. 2020) and limitations in hydroxyl radicals in the atmosphere (caused by, e.g., wildfires) extend the lifetime of methane in the atmosphere (Cheng and Redfern 2022). Managing methane emissions from water bodies will be of utmost importance given that methane is at least 28 times more potent than CO_2, and given the feedback mechanisms that allow atmospheric methane concentration to rise synergistically with climate change. The depth, age of the reservoirs, temperature, pH, and availability of nutrients in these waters and their catchments influence GHG emissions. Integrated watershed-scale policies must be adopted for effective and sustainable emission reduction strategies, taking into account inputs from the ecosystems surrounding the watershed by entailing integrated approaches for land management, restricting nutrient loading, and maintaining and improving ecohydrological connections.

Halting deforestation and ecosystem degradation to reduce GHG emissions and help preserve water cycle dynamics is of key importance for regulation of the Earth's energy, water, carbon, and nutrient cycle dynamics. In addition, it is of high importance to invest in conservation and management of large carbon sinks in forests and agricultural soils. Restoration can also accelerate the recovery of degraded land areas, supporting or reinstating ecological processes, recovering forest structure and biodiversity (Elliott et al. 2013). However, the mitigation benefits from restoration are dependent on several factors, such as the initial level of degradation, the applied restoration methods, and the time required for recovery to take place (Mackey et al. 2020).

It is critical to address the drivers that pose limitations to conserving ecosystems in climate mitigation and development planning. Managers are often faced with challenging trade-offs to implement ecosystem protection and conservation, due to constraints in tackling the drivers of degradation, such as great demand for agricultural land, urbanization, aquaculture, and coastal development (Epple et al. 2016). Land degradation is a major contributing factor to climate change, and at the same time, climate change can exacerbate the impacts of land degradation, as some drivers of degradation, such as soil erosion, increased risk of forest fires, and increased expansion of invasive species, will be exacerbated by climate change (Kotiaho et al. 2018). These challenges can be overcome by bolstering monitoring, and reliable data evaluation and management. However, many countries still lack a holistic inventory of peatlands and wetlands, which means that degradation of these systems and the resulting GHG emissions may be missed, and that there is no incentive to prevent such degradation.

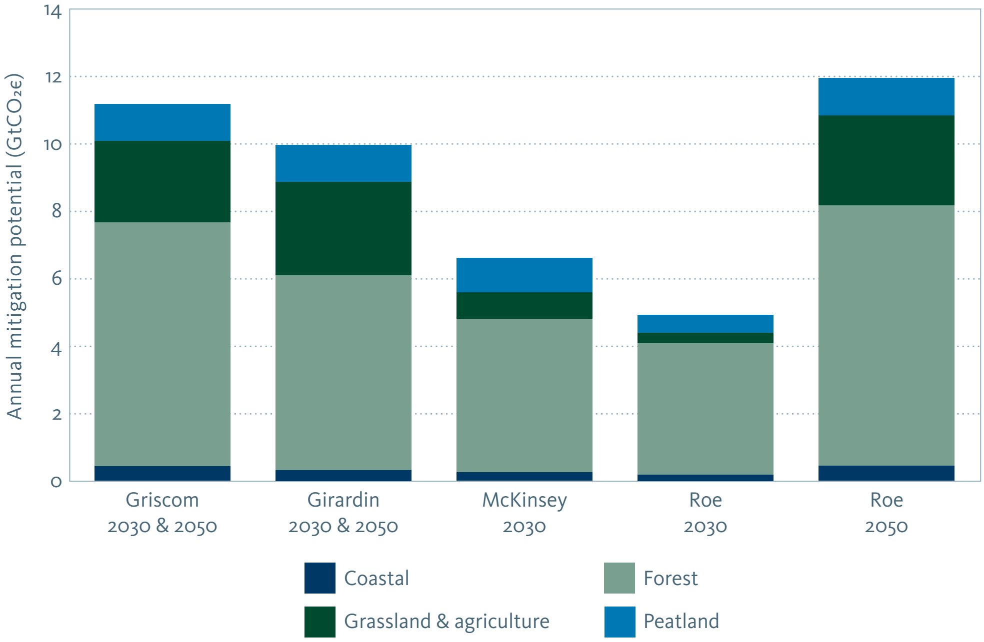

Figure 8.4. Global mitigation potential in different ecosystems. Mitigation measures in forests should be given top priority in limiting global warming, according to key studies mapping global mitigation potential in terrestrial ecosystems. (UNEP and IUCN 2021). Nature-based Solutions for climate change mitigation. Nature-based Solutions for climate change mitigation. Nairobi and Gland. https://reliefweb.int/sites/reliefweb.int/files/resources/NBSCCM.pdf

2. Action: Produce investment cases that go beyond carbon sequestration

Design NbS for mitigation, such as watershed-scale management, with the full set of ecosystem services in mind. Compared to alternative grey infrastructure development, NbS are generally found to be cost-effective while also providing co-benefits by supporting different ecosystem services (EC 2021). Still, they often require consideration of the full range of benefits provided for the return on investment to be fully appreciated (Cassin and Matthews 2021; Le Coent et al. 2021), including climate adaptation, ecosystem resilience, sustainable water management, conservation and enhancement of biodiversity, improvements in air quality, urban regeneration, and improvements in public health and well-being (Liu et al. 2021; Sturiale and Scuderi 2019).

Account for the multiple co-benefits provided by aquatic and water-dependent terrestrial ecosystems in addition to carbon sequestration, particularly in peatlands and coastal wetlands. This can include benefits for human well-being, ecosystem health, and climate resilience, such as flood and disaster risk reduction, biodiversity recovery, agricultural production, sustainable community livelihoods, water quality improvement, etc. (Raymond et al. 2017; UN Water 2018). For instance, watershed-scale aquatic system management can provide stronger cases for investment by contributions to emission reduction targets in the NDCs with multiple areas of additional value provided (Mayor et al. 2021). In addition, it is fundamental for a cost–benefit analysis to establish baseline data by ensuring the participation of stakeholders that know their environment (Le Coent et al. 2021). Although multiple co-benefits are generally provided by freshwater nature-based mitigation measures, there can be trade-offs to be considered (see Chapters 5 and 6).

8.4.3 Navigate water-wise energy pathways

Roughly 70 per cent of the water used by the energy sector goes to production of fossil fuels and thermal power generation plants (IEA 2018). Total water withdrawals and consumption for energy must be brought down from current levels to reach SDG targets with available resources. Demand and pressure on water sources could vary dramatically depending on the future energy mix and its water management. There are pathways to shift to low-emission energy that also require less water than fossil fuels and are more resilient to potential changes in the availability of water caused by climate change or increased demand from other sectors. It is important that such pathways are identified through investment and actions from governments.

1. Action: Accelerate solar and wind power where feasible

Wind and solar photovoltaic (PV) power are critically important components of the energy mix to lower pressure on freshwater ecosystems. They are fast-growing energy options that potentially have lower requirements for, and impacts on, water sources than alternatives (Lohrmann et al. 2019; Jin et al. 2019). In several scenarios designed to meet the Paris climate targets, expansion of solar and wind power and efficiency improvements will account for meeting as much as 50 per cent of energy demand by 2050 (IEA 2021; Rogelj et al. 2018; IRENA 2020). If these are not reached, there is likely to be greater demand and pressure placed on water resources from all other alternatives. Expansion of solar PV and wind power will also increase requirements for magnets, electricity storage, and batteries, as well as green hydrogen to replace and reduce requirements for fossil fuels. The corresponding increase in mining for minerals and rare earths could be both a limitation for their production, and have significant environmental impacts that need to be considered and mitigated (Elshkaki 2021).

Green hydrogen production through water electrolysis requires water to produce fuels in addition to the water required to generate the electricity to perform the electrolysis. Access and proximity to water is a fundamental requirement for green hydrogen, meaning that conversion of solar PV or wind power to hydrogen cells must be located near water sources. This could be a potential limitation on viable locations for green hydrogen production.

2. Action: Mainstream water risk assessment for energy development plans

Water must be integrated across all aspects of energy planning and development. This must be done while the transformation to clean and renewable energies is accelerated. An analysis of projected demands, availability, and impacts on water is needed to assess the feasibility of energy plans and best options at local, national, regional, and global levels. The analysis also must consider trade-offs with water demands from other sectors (e.g., agriculture) and ecosystem needs, as well as potential risks to water availability caused by climate change. Renewable energy generation that requires the operation of thermal power plants (geothermal, solar, nuclear) is highly dependent on water. This must be monitored, analysed, and managed to ensure sustainable access and limited impacts on water.

Wind and solar farm at Bac Phong, Ninh Thuan Province, Vietnam. Source: Shutterstock.

Consideration of potential impacts and constraints of water sources is especially critical in terms of the type and amount of bioenergy and hydropower that can be involved in mitigation strategies. Climate mitigation contributions from large-scale biomass production may partly fail due to water limitations, or their implementation may adversely affect water availability. It is imperative that the implications of their water and land use are considered first. This can seek to establish the maximum negative emission potential achievable with sustainable water management on both biomass plantations and agricultural areas that ensures the health of aquatic ecosystems. This can enable available water to be used more effectively, boost biomass production, and create synergies across multiple SDGs, such as food, water, and climate security (Jägermeyr et al. 2017). Stenzel (2021) highlights that substantial reductions in water withdrawals could be achieved if fewer plantations were irrigated and the carbon conversion efficiency was improved, thus enabling more production and sequestration with lower impacts on water. Effective planning, design, and management of hydropower is essential. Emissions from hydropower facilities with poor siting, design, and management can be significant (Ocko and Hamburg 2019). Evaluation should be made in advance of investment to ensure that the environmental and social costs do not outweigh potential benefits gained through the energy generated.

8.4.4 Accelerate transition to circular production and sustainable lifestyles

Efforts and investments to reduce demand for, and increase efficient use of, water, land, energy, and food resources can lead to decreased emissions, relieve pressure on ecosystems, and promote sustainable development (Rogelj et al. 2018). Two key areas to achieve this are continued innovations and improvements in circular production and solid waste management, and the promotion of sustainable lifestyles.

1. Action: Advance circular solutions in industry and waste management

Measures to reduce emissions in industrial processes and solid waste management generally provide water-related co-benefits.[1] Circular or more efficient industrial production can and should usually lower both water demand and pollution loads discharged into water bodies. Increased efficiency, safe reuse, and lower demand for water all contribute to less energy used to move and treat water, which in turn lowers emissions created by that energy use (Ramos et al. 2010). Circular water and sanitation systems that recover energy and heat from wastewater and excreta further decrease demands for external energy sources (Andersson et al. 2019). Improvements to solid waste management, with increased recycling and less landfilling and litter, provide local water benefits by lowering pollution as well as global benefits by lowering resource demands required across the lifecycle of production of the product. Reducing production of new plastic lowers emissions and pollution of water bodies and oceans. Decreased use and increased recycling of plastic reduces emissions and pollution that enter soil, freshwater, coastal, and ocean systems.

2. Action: Promote sustainable lifestyles and behaviour change

Sustainable lifestyles, including choices for housing, transportation, and food and material consumption, should be promoted to limit emissions, pollution, and resource waste. This must complement and cannot replace larger policy decisions and investments to transform our energy and agricultural systems and protect the capacity of ecosystems to mitigate emissions. Reduced demand from consumers and increased reuse of products lead to less emissions and pollution generated through industrial production, while also decreasing requirements for water for those same items being produced. There is large mitigation potential in dietary shifts to more carbon-smart and water-wise diets and in reduced food waste and loss (see Chapter 6). IPCC (2022) estimated potential reductions of 2–4 $GtCO_2E$ per year by 2030 through uptake of more sustainable diets and reduction of food losses and waste. Diets with lower portions of meat and reduced overeating particularly in the Global North and emerging economies, can result in lower emissions and water consumption required for agricultural production (Willett et al. 2019; Poore and Nemecek 2018). Behaviour changes to reduce waste are also critical as huge volumes of food are lost or wasted. Estimates from FAO (2011) noted that as much as one-third of

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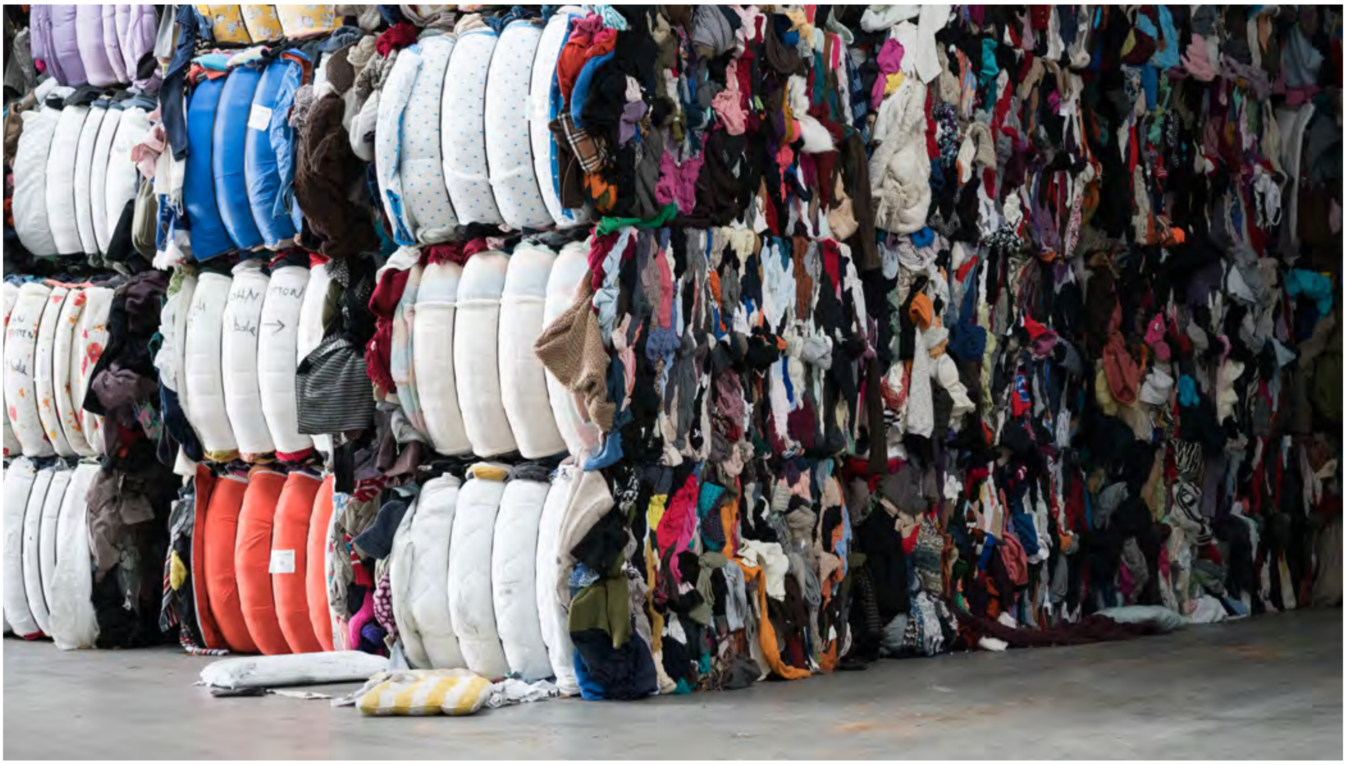
[1] One potential exception is using carbon capture storage for industry to offset emissions, which may have implications that increase water resource demand (see Chapter 7 and section 7.3.2 on BECCS).



Bales of discarded clothing at an industrial textile recycling plant. Source: Shutterstock.

food grown that is fit for human consumption is never eaten and WWF (2021) claimed in a more recent calculation that it may be as much as 40 per cent. The US Environmental Protection Agency estimates that annual production of food that is lost and wasted in the US alone utilizes an equivalent of 560,000 km² of agricultural land, 22 trillion litres of water, more than 6 million kg of fertilizer, and results in 170 million tonnes of CO_2E (EPA 2021). These figures are further amplified when the waste goes to landfill or is incinerated. Beyond food, large energy, water, pollution, and carbon footprints result across the lifecycle production of crops, goods, clothes, and all products that are wasted. The fashion sector, for example, creates 20 per cent of global wastewater and 1.2 billion tonnes of CO_2E in emissions (Chen et al. 2021), while more than 90 million tonnes of textiles are disposed annually worldwide (Kerr and Landry 2017). At the same time, increased access to nutrition, energy, and materials are needed for billions of people globally. Net-zero transitions and sustainable development globally will require nations in the Global North to consume and waste less, and developing nations are able to avoid, to the extent possible, historical trends where economic growth is followed by more resource-intensive lifestyles. Individual, government, corporate, and civil society actions are all needed to promote health and well-being and reduced material consumption to ensure future water and climate security.

8.5 Conclusions

This chapter presented key opportunities to effectively mitigate emissions through measures taken in water and sanitation services, the protection, restoration, and management of terrestrial and aquatic ecosystems (forests, river systems, wetlands), and renewable energy transition. Essential areas were identified for investment and action to enable benefits for both water and climate mitigation critical for sustainable development in the coming decades. Key water risks were highlighted that must be evaluated in low-emission energy development, particularly in the planning of bioenergy, hydropower, and other sources such as thermoelectric plants used in nuclear and concentrated solar power. The chapter also provided insights to where ecosystem degradation can create risks to reduce sequestration potential of freshwater- and land-based mitigation measures or lead to emissions of GHG.

To ensure a resilient, robust, flexible, and water-wise transition, four key leverage points should be integrated as foundational pillars to climate mitigation planning:

1. **Sustainable, low-carbon water management and sanitation services should be considered as part of plans to achieve emission reductions.** This could

include development of watershed-scale emission reduction strategies and upscaling of substantial opportunities to reduce emissions and recover energy in water and sanitation services, building on existing technologies and project know-how. This is also a first step to address gaps to mainstream water into mitigation financing and policies.

2. Investment in NbS and healthy ecosystems to store carbon and prevent disastrous release of GHG that follows ecosystem degradation. This requires efforts to protect, restore, and sustainably manage aquatic and terrestrial ecosystems such as wetlands, peatland, and forests, and to ensure healthy water cycles necessary for these ecosystems' ability to provide these services. Political action is needed to address the core drivers of ecosystem degradation in agricultural, urban, and coastal development. Expanded science can facilitate these investments and actions. More systematic analysis is needed to comprehensively quantify how changes in the water cycles and in water availability affect the carbon sequestration capacity of ecosystems worldwide. Improved inventories of all freshwater systems – peatlands, wetlands, rivers, and streams – would enable countries to invest in their ability to sequester emissions. Much more attention to emissions and sequestration from rivers and streams is particularly important as relevant data are commonly missing and can result in a failure to connect pollution of water bodies with their implications on the climate. Investment cases for NbS must then be made that include benefits beyond sequestration.

3. The transition to low-emission or renewable energy needs to be accelerated and be water-wise. Different pathways for the energy transition can either have potential to reduce pressure on water sources or dramatically increase water demand. Chapter 7 recommended key considerations for sustainable and resilient water, energy, and climate planning. First, to accelerate relatively low-water-demand energy options, such as solar PV and wind power, where feasible. Mainstreaming and continually improving water risk assessment for renewable or low-emission energy development plans is also essential, particularly to ensure the sustainability of bioenergy, hydropower, and thermal power generation development. Failure to lower emissions rapidly will require exponential increases in carbon sequestration. An overreliance on BECCS, as projected in scenarios where there is failure to rapidly curtail emissions, can lead to untenable requirements for water (Stenzel et al. 2021).

4. The final lever for water, climate, and development will be **making advances in circular economy, production, and sustainable lifestyles.** This can present win-wins for people, economy, and nature. It reduces emissions and pressure on water by lowering demands for freshwater from the production of food and goods.

To mitigate the risks and utilize the opportunities identified in this chapter requires immediate action and systematic approaches. Systems-thinking facilitates design of solutions to complex environmental problems through a deeper understanding of the natural and social systems in which the problem and solutions are embedded. The next chapter will turn to how water-wise climate mitigation, where risks are mitigated and opportunities are leveraged, can be achieved through integrated approaches.

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CHAPTER 9

Achieving climate mitigation through integrated and cross-sectoral approaches

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Chapter 9 Contents

Water being released from a reservoir spillway gate. Source: Shutterstock.

Highlights

- Integrated approaches address the interconnections between water and climate change mitigation, and are therefore required to achieve water-smart climate mitigation. Integrated approaches draw on systems thinking and, unlike siloed approaches, recognize the systemic and connected nature of climate and water. As such, they assess and address trade-offs and identify synergies.
- Integrated approaches include, amongst others, integrated water resources management (IWRM), the water-energy-food (WEF) nexus approach, source-to-sea (S2S), the landscape approach, and integrated urban water management (IUWM). Successfully delivering integrated approaches requires acknowledgement of the complexities across different geographical and management levels, temporal scales, and contexts.
- Governance systems need to be strengthened to deliver water-smart climate mitigation through integrated approaches. Enabling conditions include building transparency and data-based decision-making, strengthening capacity through inclusive knowledge systems, innovating finance, and enhancing governance across sectors and levels.

9.1 Introduction

We live in an interconnected world. As Chapter 8 makes clear, issues do not exist in isolation, but are intrinsically linked together in a complex system of interdependencies (Tengberg and Valencia 2018; Ostrom 2009; Folke 2006). This is particularly true regarding climate and water; to limit global warming to 1.5°C (above pre-industrial levels), it is necessary to be not only carbon smart but also water wise, as the second part of this report attests to. Water must therefore be mainstreamed into climate mitigation efforts, including the governance processes supporting mitigation pathways (Nielsen et al. 2020).

This chapter examines the pathways towards how this can be achieved. It outlines several integrated approaches that can be used as methods to achieve water-wise climate mitigation (section 9.2). Further, it analyses factors that need to be taken into consideration when implementing such approaches (section 9.3.). Finally, it assesses the enabling governance conditions required to implement integrated approaches and provides guidance on the policy implications for successful implementation of climate change mitigation measures (section 9.4.).

9.2 Implementing climate mitigation measures through integrated and cross-sectoral approaches

Integrated approaches are required to achieve water-smart climate mitigation. As noted in Chapter 8, siloed approaches fail to recognize the systemic and connected nature of climate and water. As such, they are unable to assess and address risks from a holistic perspective, which further implies missed opportunities to identify synergies. Embedded in this more holistic perspective is a recognition of the need to involve multiple stakeholders and engage in participatory processes as these are key pathways towards breaking through traditional silos. As pointed out in Chapter 2, natural systems are not limited by administrative borders. As a result, water-smart climate mitigation will be strengthened through cross-sectoral and cross-border collaboration. Here, ‘cross-sectoral’ is understood to encompass collaboration across different public departmental responsibilities (e.g., water, land, energy, agriculture, environment, etc.), but also collaboration between different societal sectors (state, civil society, and economy). While governments remain accountable for driving and legislating action in both climate and water, the process of change is always co-produced (UN-Water 2020).

Different integrated approaches will be suitable depending on the issue and the context. This chapter provides an overview of some of these approaches, including IWRM, the WEF nexus approach, S2S, the landscape approach, and IUWM, each exemplified through case studies. The approaches are discussed in this order as, to some extent, it reflects a historical evolution with some approaches building upon others. While not an exhaustive list, the combined approaches demonstrate the strength of managing climate and water in an integrated manner and provide practical pathways to achieve water-smart climate mitigation.

Meandering river, north Australia. Source: Shutterstock.

9.2.1 Integrated water resources management

Box 9.1. How can IRWM contribute to implementing climate change mitigation measures?

- **An approach to understand and plan for the relationship between natural and social systems.** The IWRM approach emphasizes that our natural environment is affected by the social systems that govern them. Drawing on this method can reveal how political structures can alter natural systems, including those critical to climate change mitigation.
- **A model to unveil interconnections between watershed health and other natural systems.** The IWRM approach does not explicitly address climate change mitigation. However, national IWRM plans are often linked to other interventions such as conservation of ecosystems and biodiversity, or development of water infrastructure. These provide entry points to implement climate change mitigation measures.
- **A pathway to design participatory governing structures**. IWRM as a method advocates for the inclusion of a wide range of stakeholders, including gender considerations, in governing processes. Following this method helps to mobilize communities and generate action for climate change mitigation.

IWRM started to gain traction around the time of the 1977 United Nations Water Conference in Mar del Plata (Schoeman et al. 2014). While also mentioned at the Copenhagen Preparatory Conference on Water Resources Management in 1991 and the Rio Conference in 1992, it was the Dublin Conference on Water and Development in 1992 that firmly institutionalized the approach through the adoption of the Dublin Principles (Turton et al. 2007). The Dublin Principles state that: a) water is a vulnerable, finite resource; b) water management and development should include stakeholders; c) water is an economic good; and d) women play a central role in the management and conservation of water. Based on the Dublin Principles, the Global Water Partnership (GWP), which was established in 1996, defines IWRM as “a process which promotes the co-ordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP 2000). The Dublin Principles still provide the conceptual basis for IWRM and lie at the centre of this approach.

IWRM advocates integration of the natural system with the social system. The rationale is that the former determines the availability and quality of natural resources, and the latter shapes the use and allocation of natural resources (Jønch-Clausen and Fugl 2001). Well aligned with the broader trends of shifting decision-making from only governments to governance, IWRM calls for the inclusion of a wide range of stakeholders in governing processes (Varis et al. 2014), as well as gender mainstreaming (UN-Water 2020) (Box 9.2).

Box 9.2. IWRM in practice: The case of West Africa

A case study from West Africa serves to illustrate the value of IWRM in practice, as well as its challenges in a development context. While IWRM plans do not explicitly address climate mitigation, most examples to date include components related to the conservation of ecosystems and biodiversity, considered important for the hydrological functioning of watersheds and river basins. Considering the strong links between land management and climate mitigation, IWRM plans also provide an entry point for linking IWRM with climate change mitigation.

The project Improving Water Management and Governance in African Countries through Support in Development and Implementation of IWRM Plans was approved in 2007. It was implemented by the United Nations Environment Programme-Danish Hydraulic Institute Centre for Water and Environment in partnership with national institutions in charge of water resources in the participating countries, the Economic Community of West African States and its Water Resources Coordination Centre, and the Global Water Partnership in West Africa. It was funded by the European Commission. It focused on assisting seven West African countries with strengthening their IWRM processes to reach targets set out in the Johannesburg Plan of Implementation. The project succeeded in developing four IWRM roadmaps (for the Gambia, Guinea, Guinea Bissau, and Sierra Leone), and three IWRM plans (for Côte d'Ivoire, Liberia, and Togo).

Several lessons can be drawn from the project by comparing the progress in implementing IWRM in each country:

- **The strength of existing institutional structures matters** in terms of being prepared to implement IWRM processes. While most countries in the project mainstreamed IWRM into their socio-economic development frameworks, preparedness and readiness varied among the countries, with Guinea and Guinea Bissau being the least ready and prepared for the IWRM process.
- **It is important to gain high-level political support** to move the IWRM process forward. This is illustrated by the progress made in Togo where the Poverty Reduction Strategy Paper identified water and sanitation issues as among the main causes of extreme poverty, which led to the designation of IWRM as a national priority. As a result, Togo made considerable progress with policy and legal reforms in support of IWRM. IWRM also enjoyed high-level political support in Liberia, where there was considerable progress in mobilizing and identifying funding to implement the IWRM plan. This lesson also emphasizes the need for continuous awareness raising among policy- and decision-makers of the benefits of IWRM to avoid losing momentum in connection with elections, or changes in political leadership.
- **Working through partnerships** that involve institutions from global, regional, and national levels (as in this context) is a productive way to reach IWRM targets since it enables the provision of combined technical and policy support to countries.
- **Linking IWRM to practical interventions**, such as conservation of ecosystems and biodiversity, or development of water infrastructure, more resources can be mobilized for the IWRM process. For example, in Côte d'Ivoire, IWRM was linked with hydrological infrastructure development, which led to the mobilization of additional funding including from the private sector (Tengberg 2012). Making these connections also provides an entry point for linking IWRM with climate change mitigation.

9.2.2 The water-energy-food nexus approach

Box 9.3. How can the WEF nexus approach contribute to implementing climate change mitigation measures?

- **An approach to address mitigation beyond the water sector.** The WEF nexus provides an approach to addressing mitigation beyond the water sector by taking into account synergies and trade-offs between sectors, and creating strong links between mitigation and adaptation by boosting the efficient use of resources.
- **A starting point to assess water, energy, and food jointly.** As climate mitigation measures impact freshwater, this approach provides a starting point from which the interdependence of water, energy, and food can be jointly assessed. Addressing the management of these resources simultaneously incentivizes an increase in energy efficiency in the water and agriculture sectors, reduction of the water footprint in the energy and agriculture sectors, and a reduction in the carbon footprint of the water and agriculture sectors.
- **An opportunity to make irrigation systems climate smart.** The nexus approach offers opportunities to prevent further greenhouse gas (GHG) emissions and reduce the carbon footprint of irrigation systems. This includes, for example, the use of solar pumps for irrigation or the implementation of circular models (e.g., water reuse), which help reduce water and energy consumption and strengthen the use of renewable energies.

The impacts of climate change that are manifest in water go beyond the so-called water sector to affect food security, energy consumption, and conflict over resources (GIZ et al. 2020). The WEF nexus was developed to support a more balanced approach to the various interests among sectors (Schmidt and Matthews 2018; Pahl-Wostl 2015; Hoff 2011). The WEF nexus approach seeks to consider the food, energy, and water sectors as an interrelated system (UNSGAB 2014). It thereby acknowledges that access to secure supplies in one sector has an impact on the security of supply in another. Thus, there is a need for a multi-sector approach at the systemic level to optimize supply and demand between water, energy, and food. The approach considers the totality of the available resources for food, energy, and water security and plans holistically how they can most efficiently serve human and conservation needs under a changing climate (GIZ et al. 2020). The approach started to gain traction in international discussions through the activities of the World Economic Forum Water Initiative, laying the conceptual groundwork for the WEF nexus approach (WEF 2009; 2011). It gained further momentum during the 2011 Bonn Conference, and fed into Rio+20 in 2012. The nexus lens identifies advantages concerning food security, and climate mitigation and adaptation, as well responding to possible risks such as groundwater overuse by water and climate projects by considering a holistic understanding of the interplay between sectors (Liu et al. 2018) (Box 9.4).

Solar powered irrigation system. Source: Shutterstock.

Box 9.4. WEF nexus in practice: National coordination of the users of the natural resources of the Niger basin

To contribute to climate change mitigation and support sustainable livelihoods in rural areas, the project National Coordination of the Users of the Natural Resources of the Niger basin in Niger', funded through Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) on behalf of the European Union and the German Federal Ministry for Economic Cooperation and Development (BMZ), financed a WEF security nexus pilot project. This initiative was launched in a village of 1000 inhabitants located in the Kollo department of Tillaberi region. The village faces a range of challenges, with one of the most severe being a lack of access to water. Therefore, the project supported a female cooperative of 180 women, who manage 2 hectares of land for crop cultivation. However, successful crop cultivation has been hindered due to water scarcity and uncertainty impacting the irrigation of the land particularly during the dry season.

Therefore, following a participatory approach working closely with the female cooperative, the nexus project focused on providing an irrigation system. This includes the implementation of solar pumping as well as capacity-building to enable the sustainable use of the system. Four boreholes equipped with four solar pumps, a Californian grid, and four solar fields with a total of 22 solar panels, three generators and four tanks were installed as part of a hybrid system. The solar panels are used to pump and fill the tanks using solar energy (or the generator) to pump water from the borehole to the storage tank. The water in the storage tank is released for irrigation by gravity with pressure depending on the height difference between the tank and the irrigated area. In case of poor solar energy coverage, generators can take over. This approach promotes clean energy and the sustainable use of water resources to enhance food security and mitigate resource-related conflicts through an increase in agricultural production and improved market access.

Several lessons can be drawn from the project:

- **Irrigation through solar pumps offers significant mitigation potential**. A significant amount of energy (and depending on the source of energy, carbon emissions) is needed to abstract, supply, and treat water (GIZ et al. 2020). Concerning agricultural activities, an increasing demand for irrigation caused by the need for higher food production and climate change leading to diminishing supplies of freshwater can be observed. However, in many rural regions grid electricity is not accessible or available only sporadically. Diesel and electricity costs and unreliable services therefore drastically impact farmers' irrigation capacity. Solar water pumping offers an alternative solution that contributes to climate mitigation efforts (FAO and GIZ 2018). Solar pumps do not emit GHGs and therefore contribute directly to reducing the carbon footprint of irrigation.
- **Consideration of possible risks of groundwater extraction and capacity-building are key.** Particularly in water-scarce areas and areas in which erratic rainfall patterns caused by climate change will intensify dry periods, mobilizing groundwater resources through solar pumps not only contributes to mitigation measures but also enables climate change adaptation. The nexus approach highlights the need to analyse the interplay of sectors and consider potential negative effects. When dealing with solar pumps it becomes essential to consider the danger of over pumping. The hybrid pumps will operate with low marginal costs as solar powered devices do not bear cost per unit of power once they have been installed since they are powered by the sun. The lack of financial incentives to save energy for pumping might support unsustainable water management, including wasteful water use and over pumping of groundwater resources (FAO and GIZ 2018). That is why sustainable extraction of water and maintaining the health of the aquifer is of central importance to the sustainability of the project. Various measures have been implemented to ensure that only the necessary water is pumped without causing a negative impact on the water table. Next to sensitizing the users is the coordination and strengthening of the local water authorities, which are responsible for groundwater monitoring in the region. Only their approval followed by regular field visits can assure sustainable resource use. In collaboration with the authorities, the project identifies possibilities to improve groundwater monitoring, through control wells for instance. Capacity-building is a strong focus of the project. Specifically, the project contributes to building the capacity of beneficiaries in innovative concepts for the rational use of water and energy resources, and provides agricultural inputs to increase production. Capacity-building includes training on the nexus approach, raising awareness of rational and sustainable management of water

Box 9.4. Cont.

resources, saving water and energy resources through innovative cultivation techniques, and environmental protection.

- **WEF nexus approach enables wider impact addressing regional risks and opportunities.** The WEF nexus approach goes beyond climate mitigation and adaptation measures within the water sector to promote a holistic concept to face challenges in the regional context. The case study considers women to be at the centre of economic and social recovery in this region, which is affected by terrorist violence and climate risks. This project promotes clean energy and the sustainable use of water resources to enhance food security through an increase in agricultural production and improved market access by providing training on value chain activities. Once accomplished successfully, the experiences will inform activities further afield.

9.2.3 The source-to-sea approach

Box 9.5. How can the S2S approach contribute to implementing climate change mitigation measures?

- **An approach to assess upstream and downstream relationships and implications for resource management**. The S2S approach facilitates complete evaluation of trade-offs and enables identification of co-benefits of mitigation measures across the system. For climate mitigation, such an approach is highly relevant when considering mitigation actions because the flows on which the approach focuses can be altered by climate change but can also affect it.
- **A model for governing across sectors**. The S2S approach was created as a response to traditional governance frameworks that are often structured around individual segments of a system and/or focused on one sector. To achieve climate mitigation, it will be necessary to move beyond sectoral approaches and S2S can provide a model for achieving this in practice.

The S2S approach aims to provide a holistic alternative that features the complex relationships within a source-to-sea system and addresses the need for coordination to confront the upstream and downstream implications of resource management, an aspect critical to consider in relation to both climate mitigation and adaptation. A source-to-sea system or continuum is the land area that is drained by a river system, its lakes and tributaries (the river basin), connected aquifers, and downstream recipients, including deltas and estuaries, coastlines and near-shore waters, the adjoining sea and continental shelf, as well as the open ocean (Granit et al. 2017). The linkages that are important to consider as part of climate mitigation can be described as six key flows: water, biota, sediment, pollutants, materials, and ecosystem services (Granit et al. 2017). This broad perspective is important for climate mitigation because it allows a more complete evaluation of trade-offs and enables identification of co-benefits of mitigation measures across the system (Pharr et al. 2019). Additionally, it is highly relevant when considering mitigation actions because the flows on which the approach focuses can be altered by climate change but can also affect it. Climate actions such as building reservoirs and dams affect sediment flows to the sea; this contributes to the erosion of riverbeds and coasts and the starvation of deltas downstream. These impacts combined with sea-level rise can have serious consequences on the flows and the system. However, the flows can have an impact on climate change as the carbon sequestration potential of the ocean is affected if the water quantity that reaches the ocean is greatly reduced or if it is highly polluted.

The S2S approach addresses the links throughout the system and provides a structured process for the design, planning, implementation, and evaluation of projects and programmes with the goal of supporting source-to-sea management (Mathews et al. 2019). The approach was created as a response to traditional governance frameworks that are often structured around individual segments of a system and/or focused on one sector. This can result in benefits for one sector, or in one source-to-sea segment, with negative consequences on other sectors, often making traditional governance frameworks poorly suited for managing the source-to-sea system as a whole.

The approach includes six steps (Figure 9.1), through which linkages between source-to-sea segments and sectors are considered to identify and prioritize issues to be addressed across the system (Box 9.6). The approach begins by understanding the pressures and drivers of altered key flows (Mathews et al. 2019). This, in combination with selecting an appropriate scale of intervention, engagement of stakeholders (both upstream and downstream), and a thorough understanding of the governance context sets the basis for defining a theory of change to guide planning of the intervention and implementation. Monitoring and adaptive management is used to refine the theory of change and ensure continuous improvement toward long-term outcomes. Increased collaboration and coherence among stakeholders across the source-to-sea system is critical to manage key flows that connect land, freshwater, coasts, and oceans, and to avoid jeopardizing mitigation targets and other negative impacts. The importance of confronting fragmented governance across sectors and jurisdictions when implementing climate actions in the ocean and cryosphere was highlighted by the 2019 Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere (IPCC 2019).

The S2S approach in practice: Examples from different geographies

The S2S approach is starting to be implemented around the world, for example in Brazil (IUCN 2021), Central America (GEF 2018), Southern Africa (ORASECOM 2021), and Ethiopia and Vietnam (Groeneweg Thakar and Mathews 2020). For example, GIZ, the Stockholm International Water Institute (SIWI), and International Union for Conservation of Nature are working with local stakeholders to implement the approach to address the problem of sediment and plastic waste leakage from river basins to recipient waters in Hawassa, Ethiopia and Hoi An, Vietnam. The activities were initiated in 2019 and, while not targeting climate mitigation specifically, they provide valuable lessons that are also applicable to mitigation efforts. Specifically, activities include efforts to improve coordination among local stakeholders from source to sea and increase commitments for collective action to identify and address downstream impacts from activities in the basin. A key feature of the approach is to bring together different sectors and stakeholders across a geographical area that is not always consistent with administrative jurisdictions (e.g., national or municipal borders).

Several lessons can be drawn from the project:

- **It is critical to bring together different sectors and stakeholders across a geographical area.** This is also where the most effort is needed in early stages of application.
- **The approach has proven valuable in terms of building on local knowledge** through its participatory focus. The development of a baseline analysis of the key governance instruments and institutions influencing decisions on the source-to-sea flow in question has been able to quickly convey areas where enhanced collaboration is needed.
- **The flexibility of the approach has also proven valuable.** It can be applied easily to different contexts; for example, a river basin and downstream coastal and marine areas, or an endorheic (closed) system in a landlocked country.
- **Applying the S2S approach requires local commitment**, adequate funding, and time to engage key stakeholders in a defined geographical area and to carry out all stages of the process.. Experiences in applying the approach are analysed in workshops, studies, research papers, and webinars facilitated by the Action Platform for Source-to-Sea Management (S2S Platform, 2022).

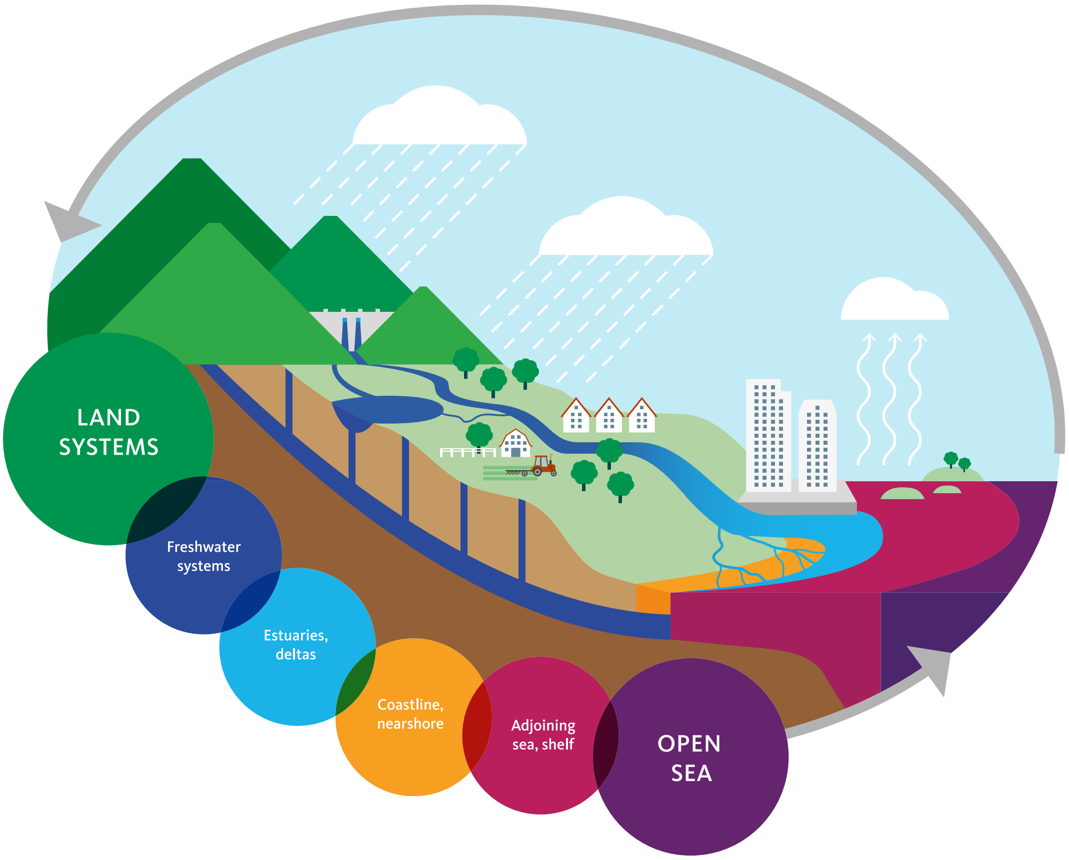


Figure 9.1. The six steps of the source-to-sea across the land-freshwater-marine continuum. Source: The Action Platform for Source-to-Sea Management.

9.2.4 The landscape approach

Box 9.7. How can the landscape approach contribute to implementing climate change mitigation measures?

- **An approach to understand system interactions.** A landscape will hold potential to implement a range of mitigation measures within the boundaries of that landscape, with some options implying trade-offs and others win-wins for climate mitigation and wider landscape health, including freshwater systems. Following the landscape approach will provide a pathway to assess these synergies and trade-offs within the system.
- **A model to adapt management to different contexts.** The delineation of what constitutes a landscape will differ depending on common problem entry point. The landscape approach can thus provide a model for adapting management to different scales and contexts.
- **A pathway for stakeholder interaction**. The landscape approach provides a pathway for dialogue and discussion among multiple stakeholders regarding trade-offs within a landscape to mobilize better land use and water resource outcomes, as well as maximizing climate mitigation potential.

Applying the landscape approach is considered particularly useful when integrated solutions are required to solve complex challenges related to sustainable development (Box 9.8). Reed et al. (2016) defined the landscape approach as a framework to integrate policy and practice for multiple land uses within a given area, to ensure equitable and sustainable use of land while strengthening measures to mitigate and adapt to climate change. Landscape approaches can be a mechanism for dialogue and discussion among multiple stakeholders regarding trade-offs to mobilize better land use and water resource outcomes. The 10 principles for a landscape approach adopted by the Convention on Biological Diversity to reconcile agriculture, conservation, and other competing land uses are: a) continual learning and adaptive management; b) common concern entry point; c) multiple scales; d) multifunctionality; e) multiple stakeholders; f) negotiated and transparent change logic; g) clarification of rights and responsibilities; h) participatory and user-friendly monitoring; i) resilience; and j) strengthened stakeholder capacity (Sayer et al. 2013).

Despite ambitious attempts to implement the landscape approach, many have failed to be truly holistic and cross-sectoral, and incorporate a multi-stakeholder perspective, and they have not been informed by local knowledge and livelihood priorities in the framing of sustainability and actions (Zanzanaini et al. 2017; Kusters et al. 2018). One of the challenges of the landscape approach is that it is based on the principle of a menu, and so does not present a framework for testing theories and relationships. Moreover, given the range of principles, most forms of environmental governance could be classified as a landscape approach (Erbaugh and Agrawal 2017), which gives rise to many interpretations and definitions. Long-term studies of forest Landscape Restoration (FLR) highlighted the importance of a conducive enabling environment, including tenure and ownership; clear rules and regulations; participation, education and capacity-building; integration of science and practice; and a dynamic private sector (Eriksson et al. 2018).

However, integration of water and understanding of hydrological processes in landscapes need to be further strengthened in FLR, because addressing water management is often a key entry point to the restoration of degraded lands, and mitigation actions in the land use, land-use change, and forestry(LULUCF) sector, while contributing to improved landscape resilience and livelihoods (Tengberg et al. 2021).

Box 9.8. The landscapes approach in practice: Strengthening water and landscape governance in Ethiopia

The SIWI-Swedish International Development Cooperation Agency project Strengthening Water and Landscape Governance in Ethiopia attempts to demonstrate how to integrate water resources in FLR by linking Ethiopia's new IWRM policy and implementation plan to the landscape approach. The key in this regard is to recognize and assess all relevant ecosystem services provided by river basins and their landscapes, and link participatory land-use planning that supports FLR to basin and sub-basin planning in maintaining the provision of critical ecosystem services, such as the provision of food, energy, and freshwater; the regulation of hydrological flows; the carbon and nutrient cycles; and cultural services, such as recreation and tourism (Tengberg et al. 2020). This approach is being demonstrated in the Ethiopia Central Rift Valley Lakes Basin and its four sub-basins of endorheic lakes.

Key lessons from Ethiopia include:

- The long-term changes in land use and land cover observed in the Ethiopian Central Rift Valley are the leading contributors to the decline and loss of ecosystem services (Mekuria et al. 2021a). This suggests that addressing the decline in forest cover and waterbodies, the major observed changes, plays a vital role in improving ecosystem services that can in turn contribute to climate change mitigation through carbon storage and sequestration.
- Identifying actions to address catchment and landscape degradation should be embedded in an understanding of the broader governance system (Mekuria et al. 2021b), and landscape stakeholders should be empowered first and foremost to organize themselves towards the planning and implementation of landscape restoration measures.

9.2.5 Integrated urban water management

Box 9.9. How can the IUWM approach contribute to implementing climate change mitigation measures?

- **IUWM addresses cities as a key action field for climate mitigation.** Due to population growth and an increasing global share of emissions that can be attributed to urban areas, cities have become a key action field for climate mitigation. IUWM approaches are crucial to addressing arising challenges in the urban water sector while realizing its mitigation potential. Mitigation and adaptation potential need to be considered in all components of the urban water cycle, from water supply to wastewater treatment and reuse.
- **A model to make urban water more energy efficient.** The management of water and wastewater often requires energy-intensive processes. Depending on the energy source (e.g., fossil fuel) this leads to high GHG emissions. Reducing energy use of urban water and wastewater systems involves reducing energy requirements for water supply, purification, distribution, and drainage as well as wastewater collection, treatment, and disposal. Practical approaches to implementation include improving operational efficiency and adopting energy efficiency measures as well as updating pumping equipment.
- **An approach to make urban water sector emissions more tangible.** The United Nations Framework Convention on Climate Change requires all parties to submit national GHG inventories, which must include emissions, removals, and sinks. The urban water sector must measure and report its emissions as part of the national inventories in a comprehensive and transparent way.
- **A model to use circular approaches and reduce GHG emissions.** Urban wastewater management offers potential to reduce GHG emissions, e.g., through the production of biogas and its use for producing electricity. Sustainable sludge management can make an important contribution to national climate change mitigation efforts and GHG emissions resulting from biodegradation. It provides great potential to implement circular approaches that provide co-benefits in economic terms; for example, technology-based upcycling solutions like pelletizing or pyrolysis allow for the valorization of treated sludge as an alternative energy carrier/industrial fuel, industrial raw material, or compost additive.

Today, 55 per cent of the world's population lives in urban areas, a proportion that is expected to increase to 68 per cent by 2050 with 90 per cent of this increase primarily in Africa and Asia (UN-DESA 2018). Unsustainable urban growth often results in deteriorating livelihoods, increasing emissions, and environmental degradation. Urbanization also increases pressure on the urban water sector to cater for growing demands for drinking water with competing interests from the agricultural and industrial sectors (WWF 2019). At the same time, urban water and wastewater management hold large, untapped GHG mitigation potential as estimates suggest that cities are responsible for around 70 per cent of global carbon dioxide (CO_2) emissions, with transport and buildings being among the largest contributors (Rosenzweig et al. 2018). Urban water-related GHG emissions are predominantly associated with energy-intensive processes of water utilities for purifying, supplying, and treating water and wastewater as well as emissions from wastewater and faecal sludge management and discharge (GIZ et al. 2020). IUWM approaches are crucial to addressing arising challenges in the urban water sector while realizing its mitigation potential (Box 9.10). Mitigation and adaptation potential need to be considered in all components of the urban water cycle, from water supply to wastewater and reuse, as the following two examples on energy efficiency of water utilities and the sustainable management of faecal sludge show (Box 9.11).

Box 9.10. IUWM in practice: Reducing GHG emissions from urban water and wastewater management

To enable the management of water and wastewater, companies require processes with a high energy demand. Depending on the energy source used, this might lead to high GHG emissions. In addition, wastewater treatment can generate emissions of methane and nitrous oxide, which have a much stronger detrimental effect on the climate than CO_2. In many cases, energy and nutrients could be recovered from wastewater by using advanced treatment technology (GIZ et al. 2020).

The Water and Wastewater Companies for Climate Mitigation (WaCCliM) project is a joint initiative between GIZ and the International Water Association. It is part of the International Climate Initiative financed by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection. The project aims to understand water flowing into, within, and out of the world's cities to create a bridge between Nationally Determined Contribution (NDC) and Sustainable Development Goal commitments (GIZ et al. 2020). WaCCliM works with a variety of actors, including the international water and climate community, national governments, and water and wastewater utilities in Jordan, Mexico, and Peru. In addition to measuring, reporting, and reducing GHG emissions, the project's objective is to increase the utilities' climate resilience, while improving their services and reducing operational costs.

Taking a closer look at WaCCliM's partner countries, water and wastewater utilities are moving towards sustainable IUWM by improving operational efficiency and adopting energy efficiency measures. In the wastewater utility of San Francisco del Rincón, Mexico, more than 4,000 tons of CO_2 equivalent per year have been prevented from being released into the atmosphere by increasing wastewater treatment coverage and improving wastewater treatment processes. In the Jordanian city of Madaba, the Miyahuna water and wastewater utility has managed to reduce carbon emissions by around 52 per cent in a water supply system by replacing pumping equipment. The Peruvian water utility (SEDACUSCO) located in Cusco, the historical capital of the Inca empire, reduced emissions from wastewater management by about 8,200 tons of CO_2 equivalent per year, mainly by improving sludge management.

Lessons learned from project implementation:

- GHG emissions from water and wastewater emissions are relevant in climate mitigation.
- When possible, emphasize economic, environmental and social co-benefits.
- Climate mitigation may successfully be added to existing adaptation processes.
- Understanding of GHG reporting and cooperation with environment ministry are key.
- High level events and agreements can sustainably drive sector progress.

New pumping equipment at an urban wasterwater treatment plant can help reduce GHG emissions. Source: Shutterstock.

Box 9.11. IUWM in practice: Upcycling sludge for climate change mitigation, water security, and economic opportunities in Jordan

Conventional faecal sludge disposal practices, which include unsanitary storage and dumping of sludge, often have overlooked negative socio-economic and ecological consequences since they contribute to deterioration of the quality of surface and groundwater with problematic implications for water security, and human and ecosystem health. Methane formation during biodegradation also accelerates climate change through high GHG emissions (GIZ et al. 2020). This issue is particularly pressing as methane alone accounts for more than 20 per cent of current climate warming (Euro-Mediterranean Centre on Climate Change 2020). In addition, unsustainable sludge management represents a lost economic opportunity; while conventional disposal practices often generate high costs, properly managed sludge has the potential to contribute to energy generation and can be used as a material resource.

In Jordan, the common way of disposing of sludge is conventional sludge-biosolids chains. After thickening and drying, most semi-dry and liquid sewage sludge is either stored and dumped onsite or transported to landfills. The Sustainable Sludge Management project implemented by GIZ on behalf of BMZ addresses the resulting ecological and socio-economic sustainability challenges in two ways:

- First, it promotes the deployment of technology-based upcycling solutions in close cooperation with its political partner the Ministry of Water and Irrigation and other local implementing partners. In the proposed innovative sludge-biosolids chain, the sludge is thickened and dried as usual but instead of dumping it, thermal processing (e.g., pyrolysis, pelletizing) is applied to create products like biochar or pellets, which can then be sold.
- Second, the project has an economic dimension as it fosters an enabling environment for the use of the new sludge products. This includes providing guidelines for product production and use, running positive awareness campaigns about sludge products and their uses to encouraging private sector participation, and developing and stabilizing distribution channels to access national and international markets. Ensuring the marketability of new sludge products and generating revenues helps to realize the economic potential sludge has to offer.

For now, this innovative approach to sludge management will be applied in three locations in Jordan where the highest economic and ecological feasibility is proven. In the chosen test facilities, information will be obtained on the optimum operational settings for useful product configuration to create opportunities for increasing the scale of the approach.

Two key lessons can be drawn from the project:

- **Sustainable sludge management can boost mitigation efforts and realize co-benefits.** Sustainable sludge management can make an important contribution to national climate change mitigation efforts and GHG emissions resulting from biodegradation. It also offers co-benefits for safeguarding aquatic ecosystems and human health and can even contribute to adaptation efforts in regions where water security is threatened by the impact of climate change.
- **Sludge is not just waste but holds untapped economic potential.** The technology-based upcycling solutions like pelletizing or pyrolysis allow for the valorization of treated sludge as an alternative energy carrier, industrial fuel, industrial raw material, or compost additive. These uses will decrease the costs resulting from common disposal practices and give wastewater utilities the opportunity to generate additional revenue while following the idea of a circular economy. In addition, they have co-benefits for the agricultural sector as farmers, including smallholders, can use organic biochar as fertilizer or for soil improvement to achieve a more permanent supply of moisture in the soil and higher yields. Furthermore, treated sewage sludge could be considered as an alternative fuel source in steel melting ovens and cement kilns, with the resulting ash used within the cement matrix.

9.3 Management under system complexities: Scalar, spatial, and temporal considerations

The delivery of integrated approaches is associated with certain complexities that need to be addressed, including acknowledgement of the complexities across different geographical regions and management levels, temporal scales, and contexts (Figure 9.2). Integrating these considerations into governance processes implies an unprecedented opportunity to address climate mitigation in a holistic water-smart manner.

While climate change is typically portrayed as a global issue, processes impacting climate mitigation are interlinked across all scales. Global climate change is not solely a product of events happening at the global level; changes are rooted in, and linked to, a complex mix of systemic interdependencies across multiple scales. Recognizing these scalar linkages is important to aid understanding of how issues interact and materialize across different levels, and to understand the potential trade-offs, synergies, opportunities, and solutions (see Chapter 8). As issues materialize in different ways across different scales, it is critical to take a holistic perspective and recognize that while an integrated approach can lead to synergistic effects at one level, it can result in trade-offs in another.

A useful starting point, as Granit et al. (2017) suggested, is to identify the appropriate scalar starting point from which to explore interconnections. The paper highlights the fact that interconnected scales can be identified and traced from a geographical perspective by, for example, examining a water body and tracing key flows, or identifying a single issue such as emissions from a particular source and tracing impacts. An example from the water mitigation context would be to trace emissions of GHGs from wastewater, which has a particular starting point, but flows through different geographical contexts. Integration also adds complexity around the issue of how to draw management boundaries, as boundaries are not fixed but socially constructed. Also, depending on how the boundaries are conceptualized, there is not necessarily a straightforward spatial fit between management boundaries and resource boundaries (Herrfahrdt-Pähle 2010). For example, conceptual demarcation can be achieved through river systems, catchments, source-to-sea systems, and landscapes. As these systems – as well as the cross-sectoral impacts – may traverse borders, the transboundary aspect also needs to be accounted for. No matter what the scalar starting point, and the manner in which it has been delineated, Granit et al. (2017) stressed that while it is useful to identify one scale as an analytical starting point, action will most likely be necessary across multiple scales.

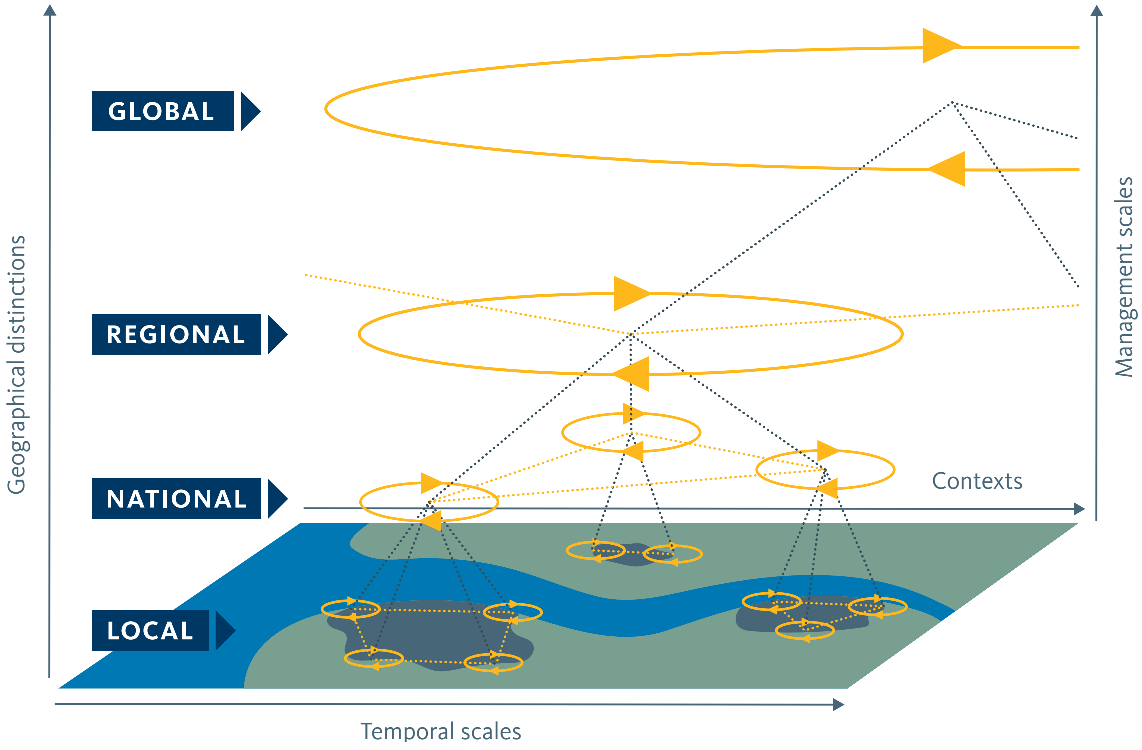


Figure 9.2. Management under system complexities. Source: SIWI.

Acting across scales creates opportunities as well as challenges. Traditionally, management approaches have been either top down or bottom up, with the former tending to be insensitive towards local realities, and the latter sometimes failing to adequately account for local contributions to global issues. Cash et al. (2006) suggest that "a middle path that addresses the complexities of multiple scales and multiple levels is much more difficult, but also what is required". Such a path needs to be nested across scales. This occurs when there are cross-level interactions between different stakeholder groups, including indigenous people, and jurisdictional bodies operating at different levels (Young 2006) (see Box 9.12.). Cross-sectoral collaboration creates challenges in terms of coordination across multiple sectors, which is inherently more complex than centralized action (Biswas 2008; Jeffrey and Gearey 2006). Moreover, it also blurs boundaries around management responsibilities. While traditional public sector approaches have clearly demarcated boundaries regarding management responsibilities, delineated through public sector responsibilities at different levels (e.g., local, regional, national), multi-stakeholder governance approaches blur these boundaries. While sectoral fragmentation and bureaucratic competition may pose a serious challenge to nesting scales (Koch et al. 2007; Lebel et al. 2011; Granit et al. 2017), it is necessary to strive towards inclusive governance approaches that can account for these different complexities and systemic interconnections through integrated approaches.

Box 9.12. Indigenous People in the NDCs: The importance of recognizing indigenous knowledge and values for climate change mitigation

Close to 38 million square kilometres of global land is located within the territories of Indigenous People, whether formally recognized or not. Many indigenous territories contain vast tracts of forested land, important water sources, and highly sustainable food systems. A recent report (FAO and FILAC 2021) noted that the forests of Latin America and the Caribbean's indigenous and tribal territories contain 30 per cent of the region's forests, equivalent to 14 per cent of carbon stored in global tropical forests worldwide. Multiple studies indicate that deforestation in indigenous territories is usually reduced compared with surrounding areas, including protected land. The report also noted that indigenous territories are under pressure from external interests. Indigenous People therefore have an outsized role in mitigating climate change, but this role is rarely recognized by national governments.

Recent analysis of the enhanced NDCs from non-Annex 1 countries revealed that close to 27 per cent included measures and activities in relation to Indigenous People or indigenous knowledge. Most references were within a context of acknowledging the marginalization or vulnerability of Indigenous People and the need for increased engagement. Very few enhanced NDCs acknowledged the potential for partnership with Indigenous People or their role in governance for mitigation or adaptation, even when forest land use plays an important role in mitigating climate change emissions within the national NDC. There were some exceptions, most notably in Belize and Costa Rica, which acknowledged a stronger role for Indigenous People in governance, but this was rare. Partnering with Indigenous People on mitigation activities and recognizing their role in governance is critical for climate mitigation, especially given the external pressures that could lead to increased deforestation or land degradation in indigenous territories. Such partnerships will need to acknowledge differences in worldviews held by partners, including differences in values and valuation approaches (IPBES 2022), as these will affect decision-making and governance.

Source: Shutterstock.

Just as spatial scale can be considered at different levels, Cash et al. (2006) showed that temporal scale can also be thought of as divided into different segments related to frequencies, durations, or rates. Both environmental and social processes occur in different timeframes, manifesting themselves as slow-moving processes as well as sudden events. When designing integrated approaches, it is therefore critical to consider alignment across timeframes; in other words, how different processes interlink and interact over time. This is important because while some actions may lead to short-term benefits, others can have long-term trade-offs or vice-versa (Folke et al. 1998; 2007; Young and Gasser 2002). It is not only important to consider the implications for natural systems, but also to recognize the standpoint of inter-generational equity.

When designing and implementing integrated approaches, consideration should also be given to contextual circumstances. Each place is different, characterized by various natural conditions, jurisdictional systems, and affected stakeholder groups, among other things (Ostrom et al. 1999). This creates a unique set of opportunities and challenges as different places experience different vulnerabilities and have various institutional structures to address these vulnerabilities. This reinforces the point that no one (integrated) approach fits all places. It also means that approaches need to be adapted depending on local circumstances and objectives as trade-offs and synergies may differ depending on the place.

9.4 Building better governance systems: Enabling conditions for strengthening integrated and cross-sectoral approaches

Climate mitigation and water are inextricably linked. Having outlined how and why different types of integrated approaches contribute to strengthening alignment between climate mitigation and water, and having discussed the complexities that need to be accounted for in these processes, this section now suggests a pathway to action. Drawing on the findings from earlier chapters, it identifies four focus areas that need to be strengthened to promote the acceleration of water-wise climate mitigation efforts: a) strengthening data-based decision-making through data generation, harmonization, and transparency; b) building capacity through inclusive knowledge systems; c) mobilizing innovative finance; and d) enhancing governance across sectors and levels.

While discussed separately, it should be emphasized that these areas are all interlinked**.** For instance, innovating finance is not an objective in its own right; it is a mechanism to deliver other objectives including building transparency and strengthening capacity. Similarly, capacity is built with a purpose, including enhancing governance and improving the nature of data. Each area is discussed below, and key recommendations for policy action within each area are outlined.

9.4.1 Strengthening data-based decision-making through data generation, harmonization, and transparency

Access to robust data that in many cases underpin management is still a challenge. Part II demonstrates that there is significant room for improvement when it comes to improving data, harmonizing accounting methodologies, and building transparency.

Several chapters demonstrate a critical need to improve the quality and coverage of scientific knowledge and data to enable mainstreaming of water into climate mitigation. For instance, Chapter 4 concludes that critical information and reporting gaps lead to probable underestimation and under-prioritization of GHG emissions from water supply and sanitation. Similarly, Chapter 5 notes that improvements in data collection and coverage have a key role to play in ensuring that inland water bodies, wetlands, and coastal systems are included more often within GHG inventories. Moreover, Chapter 6 flags that the lack of data on the relationship between forest change and water cycle dynamics at the scale of a river basin and higher reduces the capacity of managers and policy-makers to make informed, evidence-based decisions. These examples all point towards the need to improve data quality and coverage to enable scientifically robust decision-making.

Findings from Part I and II also illustrate that even when data sources are available, they are often fragmented and incomparable; there is a strong need for harmonization across accounting methodologies to ensure consistency. Specifically, different approaches to water and mitigation accounting can lead to different conclusions regarding water use or mitigation potential. Chapters 3 and 4, for example, show that there is no clear system for accounting for emissions emerging from water bodies, leading to vastly divergent estimates of both emissions and the mitigation potential of actions to reduce or prevent those emissions. Overall, the report concludes that the mitigation potential of water is likely to be significantly underestimated as a result of the ways in which emissions accounting and reporting are performed, and the lack of coherent accounting methodologies. If emissions of GHGs resulting from nutrient pollution in water bodies are not currently accounted for in a given region (Chapter 5), the mitigation benefits of removing or preventing this pollution and resulting emissions will also be difficult to track or claim.

Even when data are available, there is often a lack of transparency and sharing. Sharing is needed both between sectors and government entities, as well as across national boundaries. Access to information is an important precondition for targeted interventions. It is also a key element to stimulate functioning institutional arrangements. However, the institutional and technical structures to enable sharing across sectors, departments, and borders are still insufficient. All these aspects need to be addressed.

Strengthening data-based decision-making: Policy implications for more successful implementation of climate change mitigation measures

- **Strengthen disclosure, as well as the scientific knowledge underpinning the generation of robust data.** Knowledge gaps exist that need to be closed. Develop incentives to foster collaboration with universities and other research institutes, as well as the private sector, to drive disclosure as well as cost-efficient data collection.

- **Build institutional and citizen capacity to strengthen data collection, management, and sharing capacities.** This includes improving frameworks and knowledge to better utilize digital solutions and data management systems, and support transparency. It also includes building capacity towards developing integrated and cross-sectoral data collection and monitoring systems.

- **Invest in institutions that can collect, manage, and share data.** Invest in the development of technologies that can be used to acquire standardized data sets worldwide, targeting long-term, continuous, large-scale, and aggregated data that can be measured simply and at low cost.

- **Ensure that what is measured is also comparable.** To ensure that data can underpin decision-making, accounting frameworks need to be standardized across sectors and countries.

- **Ensure that what is measured can also be shared.** Target the development of cross-sectoral and international reporting systems to ensure access to available information. Ensure that national efforts are aligned with global systems to avoid unnecessary work.

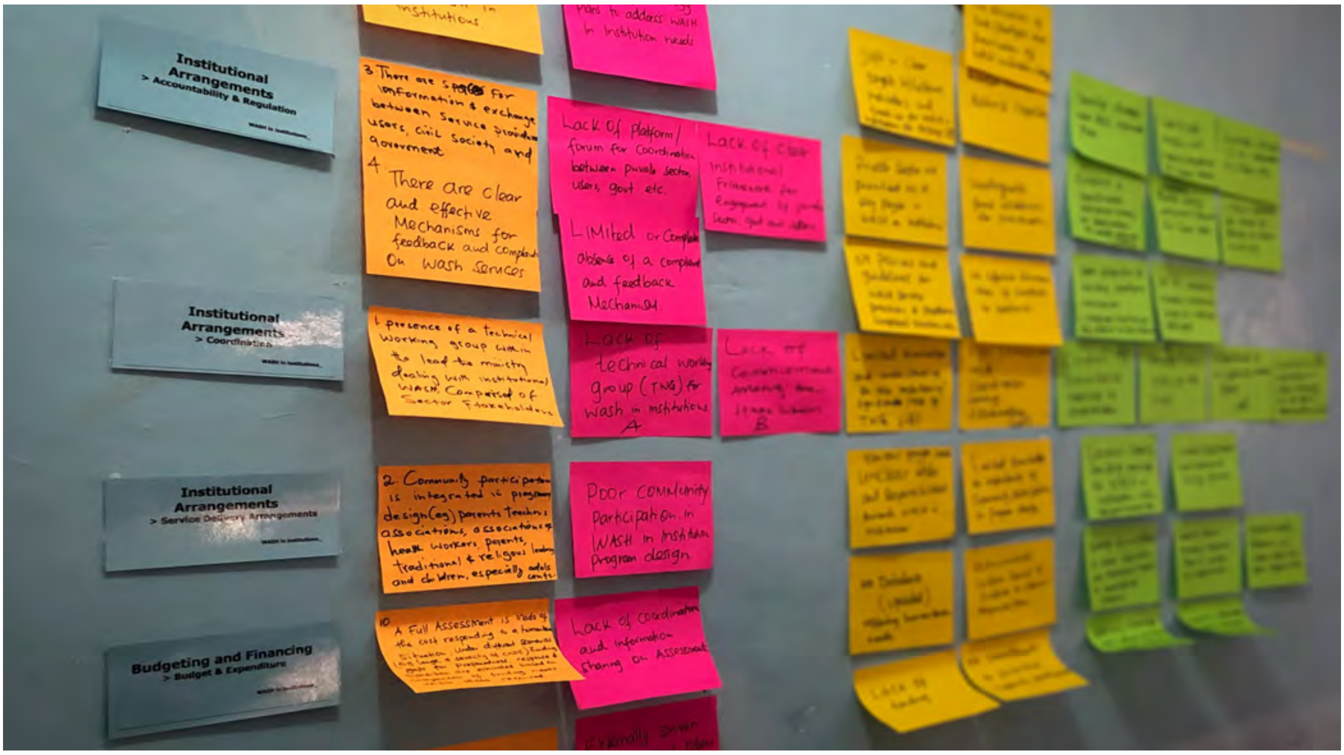
9.4.2 Building capacity through inclusive knowledge systems

While access to robust data is critical to strengthen integration and enable cross-sectoral approaches, building capacity to gather, understand, analyse, and utilize the data is equally important. The chapters in Part II point to two critical gaps in capacity: a) gaps in knowledge to fully comprehend cross-sectoral linkages; and b) insufficient capacity to address the challenges or utilize the opportunities such interlinkages present.

Building capacity to better understand the increasingly complex interdependencies across scales and actors is fundamental. This report concludes that in climate mitigation, the role of freshwater is stronger and more diversified than has been acknowledged. A great majority of mitigation measures worldwide – including in forests and grasslands, food systems and energy systems – have a link to water management and water availability in ways that must be understood and planned for. Moreover, the report shows why and how the mitigation potential of water is likely to be significantly underestimated depending on the ways in which emissions accounting and reporting are performed. Building capacity to strengthen and integrate knowledge is therefore critical. At the widest level, capacity can be strengthened by learning across governance systems. Chapter 3 concludes that to galvanize action for water-wise climate mitigation, existing governance regimes should be leveraged. More specifically, the chapter shows that strong global frameworks exist for climate action, and robust national plans often exist for water management. Building on existing institutional structures can strengthen capacity and ensure more rapid implementation of water-smart mitigation measures. To build capacity across governance systems, it is critical to recognize the need for reflexivity. To foster polycentricity and create governance systems that are adaptive, there is a need to embrace governance as an iterative process rather than a static end goal. The notion of reflexive governance encapsulates this notion, and points to the value of systems where learning is an embedded component, thus creating a system with the capability to evolve and adapt depending on context (Feindt and Weiland 2018).

Learning can also be strengthened by sharing knowledge across sectors. Chapter 4, for instance, argues that through training, considerable water-sector know-how can be scaled up to help water utilities lower emissions. At the individual level, it is fundamental that measures to build capacity are inclusive, paying special attention to youth, women, and vulnerable groups. It is also critical to recognize that the knowledge generated is inclusive, and that different knowledge is valued, to build inclusive knowledge systems. In this context, it is important to recognize that knowledge is not neutral and that actors are driven by particular interests. Thus, to ensure inclusivity, it is fundamental to ensure that a multitude of voices are heard, and to pay special attention to those that are typically excluded.

Part II not only points to a lack of knowledge on interlinkages but also to insufficient capacity to address the challenges or utilize the opportunities such interlinkages present. To strengthen capacity to act, both Chapter 3 and Chapter 6 conclude that underlying governance systems need to be strengthened. Chapter 3 argues that water has not been adequately integrated into the current climate governance regime, particularly climate mitigation efforts, which means that opportunities to invest in and accelerate climate change mitigation through water-wise actions have not yet been capitalized on. Further, Chapter 6 notes that forest management built on functional governance, monitoring, and enforcement mechanisms can mitigate climate change and generate co-benefits, such as maintenance of watershed functions and biodiversity protection. Simultaneously, policy-making and investment planning processes need to be strengthened. In particular, such processes need to budget for capacity-building activities to ensure the sufficient technical and legal knowledge is institutionalized in order to plan, design, and implement mitigation projects.



Sharing knowledge during a capacity building workshop for water and saniation in Somalia. Source: Antoine Delepiere, SIWI.

Building capacity: Policy implications for more successful implementation of climate change mitigation measures

- **Build inclusive capacity to better understand the increasingly complex interdependencies across scales and actors.** Such knowledge is critical to leverage integrated approaches that can realize water-smart climate mitigation. Pay special attention to the voices that are typically excluded, such as youth, women, and vulnerable groups.

- **Build processes to account for the increasingly complex interdependencies across scales and actors.** Such processes could include frameworks for increased collaboration and transparency, and safeguarding the integration of the acquired capacity.

- **Foster learning through collaboration.** Knowledge exchange should be pursued across governance systems, sectors, and individuals.

- **Design governance systems that are adaptive.** The notion of reflexive governance encapsulates this notion, and points to the value of systems where learning is an embedded component, thus creating a system with the capability to evolve and adapt depending on context.

- **Strengthen governance systems and planning processes** by embedding knowledge and budgeting for capacity-building activities.

9.4.3 Mobilizing innovative finance

Additional funding will be required to support water mitigation measures and protection. The International Energy Agency estimates that many trillions of dollars will need to be invested annually to reach climate agreements and limit global warming to 1.5°C (IEA 2021). Part II shows that much of the required investment in energy, agriculture, and ecosystems to achieve mitigation must consider potential risks from or impacts on water systems and, as such, these considerations need to be integrated into the financing instruments used to deliver investments.

Several chapters in Part II highlight areas where the current level of investment is not adequate to meet current or future funding needs. Chapter 4 points to the additional investment needed for wastewater treatment, noting that most global wastewater is currently not treated adequately, and that wastewater could be a significant source of GHG emissions. The chapter also highlights the underfunded nature of sanitation services. Further, Chapter 5 flags the critical need to scale up investments in restoring and rewetting degraded peatlands, as healthy and well-managed peatlands may contribute to a reduction of at least 5 per cent in global anthropogenic CO_2 emissions. Chapter 6 notes how additional funding is required to incentivise transition into water wise and climate smart land system management, that ensures the capacity of soil and vegetation to sequester carbon, while safeguarding livelihoods for smallholder farmers.

To meet funding demands, new pathways need to be explored that can facilitate investments in and direct funding to areas that can support water mitigation measures. Current and future investment needs cannot be met solely by public financing, official development assistance, and financing channelled through funds such as the Global Environment Facility and Green Climate Fund. In addition, financing requires new approaches that can mobilize more funding from the private sector.

To achieve the desired impact and ensure that funding is channelled in a manner that supports overarching national and global climate targets, institutional structures need to be strengthened. In particular, there will be a need for public actors to strengthen collaboration, especially to ensure that the water sector does not carry the sole fiscal responsibility for delivering projects upstream with substantial climate mitigation potential. Conditions that would more easily enable public authorities to pool finance to pay for different benefits also have to be explored. However, Part II demonstrates that the current institutional structures that exist to mobilize funding are ill-equipped to mobilize funding for the cross-sectoral and integrated efforts needed to deliver climate mitigation, with water mainstreamed into climate mitigation. For instance, viewing water as an additional or core component of climate mitigation will have different implications when attracting financing. This is due to different funding bodies often having specific mandates, which dictate specific end goals into which money can flow. While this is a challenge when seeking to mobilize funding for integrated projects that may contribute to a range of different goals rather than one specific component, it can also be seen as an opportunity to leverage additional financing.

Chapter 3 argues that existing climate governance regimes should be used to leverage financing for water management actions that contribute to climate change mitigation. Water has yet to be adequately integrated into current climate mitigation plans, which means that opportunities to invest in and accelerate climate change mitigation through water-wise actions have not yet been capitalized on. However, such efforts will require additional capacity-building. For example, Chapter 4 demonstrated how considerable water-sector know-how can be scaled up for water utilities to lower GHG emissions as available guidance and technologies for energy-efficient and low-climate-impact wastewater processes can be scaled up via investment and training. Further, Chapter 5 suggests that capacity-building will be a critical component to materialize implementation of bolder emission reduction targets as part of broader water resources management strategies. This strengthens the argument that each of the enabling conditions should be viewed as interconnected rather than separate.

Mobilizing innovative finance: Policy implications for more successful implementation of climate change mitigation measures

- **Foster and incentivize innovative financing models** that can attract commercial and non-commercial sources of funding.
- **Pay special attention to ensure that funds are distributed in an inclusive manner, and that investments benefit the most vulnerable.** It is critical to not exclude vulnerable communities and groups.
- **Improve the enabling conditions for fostering investments.** These include improved transparency and policy coherence to strengthen the bankability of projects.
- **Build capacity to improve know-how of the value of integrated approaches** and how to use this knowledge to leverage water and increase the scale of climate financing. Consider especially the interdependencies and mutual (financial) benefits between water and other sectors in investment planning.
- **Build institutional capacity that is equipped to fund integrated approaches,** moving beyond siloed projects by aligning frameworks across sectors.

9.4.4 Enhancing governance across sectors and levels

Governance is the primary vehicle through which to solve complex global environmental challenges. The delivery of water-smart climate mitigation requires strengthening of existing governance frameworks and instruments. The findings from Part II highlight two particular areas that need to be considered: a) one size does not fit all, implying there is a strong need to adapt governance frameworks and instruments to different scales; and b) there is a need for integrated and multi-actor governance approaches.

The need to enhance governance across different levels is a recurring theme across many of the chapters in Part II. Chapter 4 stresses the critical need to adapt to local contexts and develop locally grounded solutions. It concludes that decentralized sanitation solutions resting on local governance should be lifted as win-wins for development and climate mitigation. At the other end of the spectrum, Chapters 5 and 6 stress the need for watershed-level governance, with Chapter 5 proposing that watershed-scale policies should be adopted for an effective and sustainable emission reduction strategy, and Chapter 6 arguing that climate mitigation associated with forests and forestry needs to account for the whole water cycle, including upstream and downstream users, as well as between upwind and downwind rainfall receivers. The findings clearly demonstrate that no one approach fits all cases, but rather that governance frameworks and instruments need to be adapted to fit local circumstances.

The chapters in Part II also point to the need to enhance governance across sectors. In particular, the chapters stress the need for additional coordination and collaboration. Chapter 6 points to the need for coordinated planning, and stresses that effective emission reduction strategies will entail coordinated approaches for land and water management, while also considering factors such as disaster risk reduction, biodiversity recovery, and sustainable community livelihoods. To improve coordination in terms of goal setting, Chapter 5 calls for cross-referencing, assessing, and aligning policies, such as National Adaptation Plans (NAPs), National Biodiversity Strategies and Action Plans (NBSAPs), integrated coastal zone management, marine spatial planning, and hydrological management, to utilize synergies. Stressing the need for further collaboration, Chapter 6 argues that regional and cross-border collaboration may help address water trade-offs as well as undesirable transboundary deforestation leakages. As noted in Chapter 3, collaboration across sectors is also critical to adapt to the growing number of non-state actors involved in governance. While governments undoubtedly remain the drivers of regulation, more actors are taking a larger role in policy design and implementation, broadly characterizing the shift from government to governance as a system of governing. Chapter 3 further notes that this shift towards such polycentric governance systems is necessary because to perform well under conditions of rapid climate change, governance systems must be integrated (coordinated across levels and sectors to enhance synergies and reduce trade-offs) and adaptive (able to respond to new knowledge gained during policy implementation) (Pahl-Wostl 2015).

Enhancing governance: Policy implications for more successful implementation of climate change mitigation measures

- **Capitalize on on-going water and climate governance processes across different levels** to further integrate the water and climate agendas.
- **Pay special attention to ensure that governance frameworks and instruments are adaptive** to suit the needs of different contexts and different scales.
- **Design governance frameworks that enable and support integrated approaches**. In particular, align planning and goal setting to leverage synergies across sectors where relevant.
- **Foster collaboration across scales, sectors,** and borders and recognize the need for collaboration and coordination among different actors to leverage synergies and better support context-specific and cross-sectoral challenges; for example, by supporting cross-sectoral and multi-stakeholder dialogues.
- **Build capacity within governance systems** to support data collection, management, and sharing.

9.5 Conclusion

Water must be mainstreamed into climate mitigation processes to achieve climate mitigation targets. This chapter argues that integrated approaches can help achieve water-smart climate mitigation. To make this case, Section 9.1 provides an overview of some of these approaches, including IWRM, the WEF nexus approach, the S2S approach, the landscape approach, and IUWM. Exemplifying each approach through case studies, it is demonstrated how different approaches can be utilized depending on the context. Section 9.2 further outlines the complexities that need to be accounted for in these integrated processes. Section 9.3 turns to outline the pathway for action. Drawing on the findings from Part I and II, it identifies four focus areas, including building transparency and data-based decision-making, strengthening capacity through inclusive knowledge systems, innovating finance, and enhancing governance across sectors and levels. Combined, these sections make a strong case for a pathway in which climate and water is managed in an integrated manner to achieve water-smart climate mitigation.

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CHAPTER 10

Concluding remarks: freshwater – the essential drop to reach net-zero

Mitigation cannot succeed without water

To be viable, sustainable, and ultimately successful, climate mitigation strategies must be underpinned by a clear understanding of the requirements for, and impacts upon, freshwater resources. Insufficient recognition of climate–water interactions in greenhouse gas (GHG) reporting frameworks means that water is not included in climate mitigation planning and reporting to the extent necessary. Currently, countries are not required to report on (potential) water-related mitigation action, except in the area of wastewater treatment. The historical lack of attention to the connection between freshwater and climate mitigation primarily stems from a knowledge gap: the interrelations between water cycles, freshwater availability, freshwater limitations, and mitigation of GHG emissions have not yet been clearly articulated and recognized.

Making a significant contribution to closing this knowledge gap, this report provides a comprehensive scientific overview and assessment of freshwater's role in, and for, climate mitigation, and shows that as of today, freshwater is an underestimated factor in climate change mitigation. Based on this evidence, this report identifies the following five key messages:

1. **Climate mitigation measures depend on freshwater resources.** Present and future freshwater availability needs to be accounted for in climate mitigation planning and action.

2. **Climate mitigation measures impact freshwater.** Freshwater impacts – both positive and negative – need to be evaluated and included in climate mitigation planning and action.

3. **Water and sanitation management can reduce GHG emissions.** Climate mitigation planning and action should include the substantial emission reduction potential in drinking water and sanitation services, and through the management and protection of freshwater resources.

4. **Nature-based Solutions to mitigate climate change can deliver multiple benefits for people and the environment.** Priority should be given to measures that can safeguard freshwater resources, sequester carbon, protect biodiversity, improve soil and water productivity, and ensure sustainable and resilient livelihoods.

5. **Joint water and climate governance need to be coordinated and strengthened.** Mainstreaming freshwater in all climate mitigation planning and action requires polycentric and inclusive governance arrangements that can facilitate integrated approaches.

Decentralised wastewater treatment tank and floating solar farm. Source: Shutterstock.

iSimangaliso Wetland Park in KwaZulu-Natal Province, South Africa. Source: Shutterstock.

These messages are underpinned by the comprehensive scientific review of the interdependencies between freshwater and climate mitigation included in this report. As demonstrated, water is an intricate part of the Earth system but due to current institutional setup, governance needs to be strengthened to enable water-wise climate change mitigation. The strong links between climate mitigation and water hold true across all sectors and biomes explored throughout the report: from the water to the energy sectors as well as across freshwater and land systems. Critically, the report takes a cross-sectoral and multidisciplinary perspective and identifies priority risks and win-wins for water-wise climate planning, investment, and implementation across these sectors and biomes. Specifically, it identifies how water risks could limit the success of the climate mitigation measures, and which mitigation measures could pose risks to the water cycle. Moreover, it identifies win-wins where sustainable water management and governance can contribute to reduce emissions. Four priority areas for water-wise climate action are presented. These highlight specific ways freshwater management can contribute directly to climate mitigation and therefore must be included in climate (mitigation) plans and policies. The report also argues that to mitigate risks and utilize the win-wins, integrated governance approaches are required. To make this governance transition towards managing water and climate in an integrated manner, the report points towards a number of focus areas, which must be strengthened. Specifically, this includes strengthening data-based decision-making through data generation, harmonization, and transparency, building capacity through inclusive knowledge systems, mobilizing finance to fund the cross-sectoral and integrated efforts needed, and enhancing governance across levels and sectors.

The report presents a scientifically robust case for water-wise climate mitigation. The time to act is now. Following its recommendations will ensure that freshwater is mainstreamed into climate mitigation planning and action. Similarly, climate change adaptation and mitigation measures need to remain as critical considerations in IWRM processes. For governance systems and national implementation plans to succeed, **freshwater needs to be put in its rightful place: at the heart of all efforts to adapt to, as well as to mitigate, climate change**.

We urge the climate and water community alike to respond to this call, by integrating sustainable freshwater management into climate action across all relevant sectors and biomes to accelerate net-zero.

Glossary

Glossary[1]

AFOLU. Agriculture, forestry and other land use is a grouping used in greenhouse gas accounting under the United Nations Convention on Climate Change (UNFCCC), combining the GHG inventories from agriculture with land use, land use change and forestry (LULUCF).

Agroforestry. Collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components.

Afforestation. Conversion to forest of land that historically has not contained forests. (IPCC 2019)

Biodiversity. Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

Bioenergy. Energy derived from any form or biomass (IPCC 2019).

BECCS. Carbon Capture and Storage (see CCS) technology applied to a bioenergy facility.

Blue carbon ecosystem. According to Ramsar Convention on Wetlands, Blue Carbon is the “carbon captured by living organisms in coastal (e.g., mangrove forests, salt marshes and seagrass meadows) and marine ecosystems and stored in biomass and sediments”. The coastal and marine ecosystem that captures blue carbon is referred as Blue Carbon Ecosystem (BCE) (Convention on Wetlands, 2021)

Blue Water. Refers to freshwater in lakes, rivers, and groundwater aquifers

Climate change. A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/ or the variability of its properties and that persists for an extended period, typically decades or longer.

Climate (change) mitigation. Means for reducing or capturing emissions of greenhouse gases to limit their impacts on global temperature rise and the global climate system.

Climate mitigation measures. In climate policy, mitigation measures are technologies, processes or practices that contribute to mitigation, for example renewable energy technologies, waste minimisation processes, public transport commuting practices.

Co-benefits. The positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits for society or the environment.

Convention on Biological Diversity (CBD). The Convention on Biological Diversity (CBD) is the international legal instrument for "the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources" that has been ratified by 196 nations.

CCS. A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere (IPCC 2019).

Carbon sequestration. The process of storing carbon in a carbon pool (IPCC 2019).

Deforestation. Conversion of forest to non-forest.

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1. Reference: IPCC, 2019: Annex I: Glossary [van Diemen, R. (ed.)]. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.). *Plain text produced by report authors.* *11_Annex-I-Glossary.pdf (ipcc.ch)*

Emission scenario. A plausible representation of the future development of emissions of substances that are radiatively active (e.g., greenhouse gasses (GHGs), aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and land use) and their key relationships. Concentration scenarios, derived from emission scenarios, are often used as input to a climate model to compute climate projections

Ecosystem services. Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or biodiversity maintenance, (2) provisioning services such as food or fibre, (3) regulating services such as climate regulation or carbon sequestration, and (4) cultural services such as tourism or spiritual and aesthetic appreciation. (IPCC 2019)

Floodplain. Floodplains are land areas along the watercourse. Floodplains are usually formed by alluvial sediments deposited during floods of varying magnitude and associated geomorphological processes (Jakubínský, et al., 2021).

Freshwater. Water over land in any form, including evaporation, transpiration, precipitation, atmospheric moisture, soil moisture, frozen water, surface water, and water in the technosphere. In the context of this report, we are particularly concerned about the dependence on and impact of mitigation measures on freshwater sources and freshwater-dependent systems.

Freshwater-dependent systems. Any terrestrial, aquatic, coastal, and marine ecological and social-ecological system supported and influenced by freshwater.

Global warming. An increase in global mean surface temperature (GMST) averaged over a 30-year period, or the 30-year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue (IPCC 2019)

Green water. Refers to plant-available water in the soils, or more broadly all evaporation fluxes and soil moisture on land.

Governance. A comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures.

Greenhouse gas (GHG). Gaseous constituents of the atmosphere, both natural and anthropogenic, absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth’s surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary GHGs in the Earth’s atmosphere.

Hydrological cycle. The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condenses to form clouds, precipitates as rain or snow, which on land can be intercepted by trees and vegetation, potentially accumulating as snow or ice, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and ultimately, flows out into the oceans as rivers, polar glaciers and ice sheets, from which it will eventually evaporate again. The various systems involved in the hydrological cycle are usually referred to as hydrological systems.

Indigenous knowledge. The understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. For many Indigenous peoples, Indigenous knowledge informs decision-making about fundamental aspects of life, from day-to-day activities to longer term actions.

Integrated water resources management (IWRM). A process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Lake. Lakes are characterized by standing water forming in depressions of the landscape. Lakes can also be formed by tectonic, volcanic, or riverine activity, as well as landslides, wind erosion, dissolution of limestone, or biological activity such as beaver dams (Hutchinson, 1975) (Wetzel, 2001) (Fluet-Chouinard, et al., 2018)

Landscape approach. A Landscape Approach is broadly defined as a framework to integrate policy and practice for multiple land uses, within a given area, to ensure equitable and sustainable use of land while strengthening measures to mitigate and adapt to climate change

Land use. The total of arrangements, activities and inputs applied to a parcel of land. The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation and city dwelling). In national GHG inventories, land use is classified according to the IPCC land use categories of forest land, cropland, grassland, wetlands, settlements, other lands (see the 2006 IPCC Guidelines for National GHG Inventories for details).

Land-use change. The change from one land use category to another. [Note: In some of the scientific literature assessed in this report, land-use change encompasses changes in land-use categories as well as changes in land management.

Nature-based Solutions (NbS). NbS are defined by IUCN as “actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature.”

Nationally Determined Contributions (NDCs). A term used under the United Nations Framework Convention on Climate Change (UNFCCC) whereby a country that has joined the Paris Agreement outlines its plans for reducing its emissions. Some countries' NDCs also address how they will adapt to climate change impacts, and what support they need from, or will provide to, other countries to adopt low-carbon pathways and to build climate resilience. According to Article 4 paragraph 2 of the Paris Agreement, each Party shall prepare, communicate and maintain successive NDCs that it intends to achieve.

Negative emissions. Removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, i.e., in addition to the removal that would occur via natural carbon cycle processes

Net-Zero Emissions. Net-zero emissions are achieved when emissions of greenhouse gases (GHGs) to the atmosphere are balanced by anthropogenic removals. Where multiple greenhouse gases are involved, the quantification of net-zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon).

1.5°C pathway. A pathway of emissions of greenhouse gases and other climate forces that provides an approximately one-in-two to two-in-three chance, given current knowledge of the climate response, of global warming either remaining below 1.5°C or returning to 1.5°C by around 2100 following an overshoot. The pathway concept ranges from sets of quantitative and qualitative scenarios or narratives of potential futures of natural and/or human systems to solution-oriented decision-making processes to achieve desirable societal goals (IPCC 2019).

Paris Agreement. The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in December 2015 in Paris, France, at the 21st session of the Conference of the Parties (COP) to the UNFCCC. The agreement, adopted by 196 Parties to the UNFCCC, entered into force on 4 November 2016 and as of May 2018 had 195 Signatories and was ratified by 177 Parties. One of the goals of the Paris Agreement is ‘Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels’, recognising that this would significantly reduce the risks and impacts of climate change (IPCC 2019).

Peat. Peat is classified as an organic soil, derived from incomplete decomposition of plant matter due to saturated soils, cool temperature, and acidic environment (Soil Survey Staff, 2014). Various species of Sphagnum mosses and tree species form peat in temperate and boreal regions (Inglis et al., 2015). Furthermore, organic matter that forms tropical peat is derived from diverse forest formations (Anderson, 1963; Morley, 1981).

Peatland. Peatlands are wetlands with a thick water-logged soil layer made up of dead and decaying plant material. Peatlands include moors, bogs, mires, peat swamp forests and permafrost tundra. Peatlands represent half of the Earth’s wetlands and cover 3% of the global total land area. They are found all over the world (Wetlands International, 2022).

REDD+. REDD+ refers to reducing emissions from deforestation; reducing emissions from forest degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks

Reforestation. Conversion to forest of land that has previously contained forests but that has been converted to some other use.

Resilience. The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/ or transformation

Reservoir. Reservoirs (artificial lakes) are created by impounding streams and digging shallow ponds for the purpose of flood protection, water supply, irrigation, and hydropower production, etc. (Fluet-Chouinard, Messager, Lehner, & Finlayson, 2018).

Risk. The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and well-being, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species.

River. A river is a natural watercourse, usually freshwater, flowing towards an ocean, a lake, a sea, or another river.Rivers originate as rain on high ground that flows downhill into creeks and streams. They connect to major wetland systems and deltas, which are found on the lower reaches of rivers, where the flow of water slows down and spreads out into expanses of wetlands and shallow water (Wetlands International, 2022).

Social-ecological system. An integrated system that includes human societies and ecosystems, in which humans are part of nature. The functions of such a system arise from the interactions and interdependence of the social and ecological subsystems. The system's structure is characterised by reciprocal feedbacks, emphasising that humans must be seen as a part of, not apart from, nature.

Source-to-Sea. Source-to-sea refers to the connections between what we do on land and along rivers, and the impact this has further downstream, along coasts and in the ocean. Water, sediment, plants, and animals provide such connections as does human waste and pollutants.

Sustainable Development Goals (SDGs). The 17 global goals for development for all countries established by the United Nations through a participatory process and elaborated in the 2030 Agenda for Sustainable Development, including ending poverty and hunger; ensuring health and well-being, education, gender equality, clean water and energy, and decent work; building and ensuring resilient and sustainable infrastructure, cities and consumption; reducing inequalities; protecting land and water ecosystems; promoting peace, justice and partnerships; and taking urgent action on climate change.

Sustainable forest management. The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems.

Sustainable land management. The stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions

Tidal wetlands. Tidal wetlands, often called coastal wetlands, are typically made up of organic and mineral soils that are "covered or saturated, for all or part of the year, by tidal freshwater, brackish or saline water (<0.5, 0.5-18, and >18 ppt salinity, respectively) and are vegetated by vascular plants" (Kennedy et al. 2013 page).

United Nations Convention to Combat Desertification (UNCCD). A legally binding international agreement linking environment and development to sustainable land management, established in 1994. The Convention's objective is 'to combat desertification and mitigate the effects of drought in countries experiencing drought and/or desertification'. The Convention specifically addresses the arid, semi-arid and dry sub-humid areas, known as the drylands, and has a particular focus on Africa. As of October 2018, the UNCCD had 197 Parties.

United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC was adopted in May 1992 and opened for signature at the 1992 Earth Summit in Rio de Janeiro. It entered into force in March 1994 and as of May 2018 had 197 Parties (196 States and the European Union). The Convention's ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. The provisions of the Convention are pursued and implemented by two treaties: the Kyoto Protocol and the Paris Agreement

Wetland. According to The Ramsar Convention, wetlands are "areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water the depth of which at low tide does not exceed six metres" (Ramsar Convention on Wetlands, 2016). Under this definition wetlands can include "all lakes and rivers, underground aquifers, swamps and marshes, wet grasslands, peatlands, oases, estuaries, deltas and tidal flats, mangroves and other coastal areas, coral reefs, and all human-made sites such as fish ponds, rice paddies, reservoirs and salt pans" (Ramsar Convention Fact Sheet 6, 2015). Different types of wetlands have different characteristics in terms of hydrology, ecology and their role in the carbon cycle. No single classification is likely to meet all needs of different wetland inventories, and hence it is recommended by Ramsar Convention on Wetlands to choose or develop classifications suited to the purposes of a particular wetland inventory (Ramsar Convention on Wetlands, 2002) (Anisha, et al., 2020).

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